State of California
The Resources Agency
Department of Water Resources

SP-G2: EFFECTS OF PROJECT OPERATIONS ON GEOMORPHIC PROCESSES DOWNSTREAM OF OROVILLE DAM

TASK 5 – DAM EFFECTS ON CHANNEL HYDRAULICS AND GEOMORPHOLOGY AND TASK 8- SUMMARY AND CONCLUSIONS

Oroville Facilities Relicensing
FERC Project No. 2100

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ARNOLD SCHWARZENEGGER
Governor
State of California

MIKE CHRISMAN
Secretary for Resources
The Resources Agency

LESTER A. SNOW
Director
Department of Water Resources

State of California
The Resources Agency
Department of Water Resources

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This report was prepared under the direction of

Terry Mills.. Environmental Program Manager, DWR

by

Koll Buer.. Senior Engineering Geologist, DWR
Dave Forwalter.. Associate Engineering Geologist, DWR

Assisted by

Donna Calder .... Associate Engineer, DWR
Shawn Pike .... Senior Engineer, DWR
Clint Andreasen.. Student Assistant, DWR

REPORT SUMMARY

The construction of Oroville Dam has altered the hydraulic, geomorphic, and sediment transport regimes of the Feather River. Study Plan G2 is designed to identify and evaluate ongoing effects of altered downstream hydrology and sediment retention in Lake Oroville on channel morphology and sediment transport in the Lower Feather River. Specifically, the plan will address the following components:

1. Determine sediment conditions and sediment transport requirements.
2. Evaluate sediment sources (including tributaries) and conditions.
3. Map major sediment deposits.
4. Evaluate stream channel stability.
5. Evaluate project-affected sediment regimes.
6. Evaluate timing, magnitude, and duration of project-affected flows in relation to geomorphic effects.
7. Determine the effect of the project on fluvial geomorphologic features.
8. Provide a summary of findings.

Results from these components will be used to identify limiting factors (impacts associated with biological effects) and develop a comprehensive sediment management plan for the purposes of protection, mitigation and enhancement measures to improve river form and function in the Feather River. The study results will also be used by other studies to help assess the Oroville Facilities ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources.

The study plan is organized into individual tasks and sub-tasks that are addressed in separate reports because of the amount and complexity of the data. These are:

- Task 1.1 - obtain, review, and summarize existing resource data and references;

- Task 1.2 – prepare a general description of the lower Feather River and watershed, include mesohabitat typing;

- Task 2 - map and characterize spawning riffles;

- Task 3 - evaluate changes to the channel morphology by re-establishing historic cross-section surveys and photo points;

- Tasks 6 - assess current channel characteristics and monitor selected cross-sections for significant changes to those characteristics; establish bank erosion monitoring sites

- Task 5 - determine project effects on river hydraulic and geomorphic parameters;
- Task 7 - model sediment transport and channel hydraulics; make predictions
- Task 8 – summary and conclusions.

This task report fulfills the requirements for “Task 5 - Dam Effects on Channel Hydraulics and Geomorphology” and “Task 8 – Summary and Conclusions”. The report presents the sub-tasks, methodology, and results. It presents the hydraulic, geomorphic, and sediment transport changes that have occurred as a result of human activities and the Oroville Facilities. Chapter 8 provides the summary and conclusions for Study Plan G2 task reports.

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1.0 INTRODUCTION

This report evaluates Feather River geomorphic changes resulting from the construction of Oroville Dam. The study reach begins at the Fish Barrier Dam near Oroville and extends to the mouth of the Feather River at Verona, a river distance of about 70 miles. The report identifies the hydraulic, geomorphic, and sediment transport changes that have occurred. The effect of these changes on salmonid spawning riffles, flooding, riparian vegetation, riparian habitat, and river habitat was also considered.

Changes in sediment transport will be evaluated by use of a sediment transport model. This model will also be used to predict changes in sediment transport and channel meandering resulting from various proposed flow regimes. Based on the results of the study, we will identify needs for protection, mitigation or enhancement activities. The study results will also be used by other studies to help assess and predict the Oroville Facilities ongoing effects over the next 25 and 50 years on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources.

The *Task 5 - Dam Effects on Channel Hydraulics and Geomorphology and Task 8 – Summary and Conclusions* is one of seven reports that fulfill the scope of Study Plan G2.

1.1 BACKGROUND INFORMATION

The Feather River is an important resource for salmonid spawning habitat in California, second only to the Sacramento River. The completion of Oroville Dam in 1967 reduced this habitat by blocking access to upstream reaches. This includes 25 miles to Miocene Dam on the West Branch, 21 miles to Poe Powerhouse on the North Fork, 19 miles to Curtain Falls on the Middle Fork, and 8 miles to Ponderosa Dam on the South Fork. This loss of spawning habitat was mitigated by the Feather River Fish Hatchery. The hatchery provides an artificial spawning and rearing facility for Chinook salmon and steelhead.

Oroville Dam also affects hydrology and sediment transport characteristics, altering the movement of water, sediment, and woody debris in the river. The primary function of the dam is to store winter and spring runoff for release into the river as necessary for project purposes. This results in an altered hydrologic regime that includes changes to the yearly, monthly, and daily stream flow distributions; bankfull discharge, flow exceedance, peak flow, and other hydraulic characteristics.

It also means that the reservoir along with other hydroelectric projects on the feather river captures almost all of the sediment eroded from the upper feather river watershed. This changes patterns of sediment transport and deposition, scour, mobilization of sediment, and levels of turbidity. These changes can result in the coarsening of spawning gravel on riffles, which in turn may adversely affect salmon and steelhead.

These changes to the river hydrology and sedimentation patterns will in turn alter the channel morphology. These can include changes to the channel shape, slope, capacity, meandering, and sediment transport.

These potential impacts may extend downriver from Oroville Dam to the junction with the Sacramento River and possibly beyond. These are further complicated by a long history of a variety of land uses along the Feather River including hydraulic mining, gravel mining, gold dredging, timber harvesting, water diversions, and urbanization.

1.1.1 Study Area

The Lower Feather River flows about 72 miles from Oroville Dam to the Sacramento River at Verona. The river flows past distinctive geographic and geomorphic features. These are shown in Table 1.1-1

Table1.1-1 River Miles, Valley Miles and Related Geographic Features of the Feather River

RIVER MILE (1997 USACE)	RIVER MILE (USGS)	VALLEY MILE	GEOGRAPHIC FEATURE
71.5			Oroville Dam
67.2	67.8		Thermalito Diversion Dam
66.5	67.2		Fish Barrier Dam
66.3	67.0		Table Mountain Bridge
65.0	65.6		Highway 70 Bridge
58.7	59.0		Confluence with Thermalito Afterbay Outflow
50.6	50.8		Gridley Bridge
44.3	44.0		Confluence with Honcut Creek
42.5	42.3		Live Oak
27.9	28.5	24.9	Yuba City and Marysville
27.1	27.5	24.4	Confluence with Yuba River
N/A	25.4	22.6	Upstream End of State Cutoff (1909)
N/A	22.5	20	Downstream End of State Cutoff (1909)
N/A	19.5	17.4	Abbot Lake
N/A	18.8	16.7	Star Bend

RIVER MILE (1997 USACE)	RIVER MILE (USGS)	VALLEY MILE	GEOGRAPHIC FEATURE
N/A	17.0	15.7	O'Conner Lakes
N/A	13.0	12.3	Lake of the Woods
N/A	12.5	11.6	Confluence with Bear River
N/A	9.6	9.1	Town of Nicolaus
N/A	9.3	8.9	99 Bridge (Garden Highway)
N/A	8.2	8	Upstream End of State Cutoff (post-1911)
N/A	7.5	7.3	Upstream End Sutter Bypass; Downstream End State Cutoff (post-1911)
0.0	0.0	0	Verona, Confluence with Sacramento River

More effort was spent on the 39-mile reach from the Fish Barrier Dam to Yuba City (Figure 1.1-1). Below Yuba City, the Yuba and Bear Rivers join the Feather, and the overall effect of Oroville Dam is greatly reduced. The study boundary extends laterally to the edge of the 500-year floodplain as defined by the USACE (1997).

The study reach is further divided into four subreaches based on differences in the hydrologic flow regime. The first (the Low Flow Reach) is the 8-mile stretch between the Fish Barrier Dam and the Thermalito Afterbay outflow. The second is the 39-mile reach between the Afterbay outflow and the Yuba River. The third, is 15 miles from the confluence of the Yuba River to the confluence of the Bear. The fourth, about 12 miles long, begins at the confluence with the Bear and ends at the confluence of the Feather and the Sacramento River at Verona.

Most of the SP-G2 study effort was on the salmon spawning reach between the Fish Barrier Dam and Honcut Creek. The activities included in this reach are: FLUVIAL-12 model, sediment sampling, permeability, dissolved oxygen, and temperature measurements. Below Honcut Creek, geomorphic and mesohabitat typing was done, including bank erosion, bank composition, habitat, geology, soils and woody debris.

1.1.2 Description

The Feather River watershed is mainly in the northern Sierra Nevada geomorphic province. The river drains the western slope of the Sierra Nevada and is tributary to the Sacramento River. Some of the headwaters also lie within the Basin and Range geomorphic province, containing both steep forested mountains and large intermountain valleys. The climate is Mediterranean, with mostly dry summers and wet winters. Annual precipitation ranges from 75 inches in the upper watershed to 30 inches in the lower watershed near Oroville Dam.

The Feather River is underlain by resistant metamorphic, volcanic, and plutonic rocks in the 4-mile reach downriver of Oroville Dam to the Fish Diversion Dam. It is incised into these rocks, forming steep canyon walls.

Below the town of Oroville, the Feather River emerges from the Sierra Nevada into the foothills of the Sacramento Valley. At about three quarters of a mile below the Diversion Dam, at the first major spawning riffle, bedrock is still exposed in the channel. Below Bedrock Park, the river begins to flow in an alluvial channel incised into dissected older alluvial uplands.

The Oroville Wildlife Area, consisting of dredger tailings and borrow pits, occurs from a few miles below Oroville to a few miles above Gridley. Below the dredger tailings, the river meanders through hydraulic mining debris, floodplain deposits, and older terrace deposits.

1.1.3 River Access

The river is accessible by vehicle through the Oroville Wildlife Area and public parks. Numerous public boat ramps are also available. Jet boats can often be used in the High Flow Reach and sometimes in the Low Flow Reach dependent on flow. Seasonal variations in flow can make some riffles difficult or impossible to navigate and submerged snags can be an additional hazard.

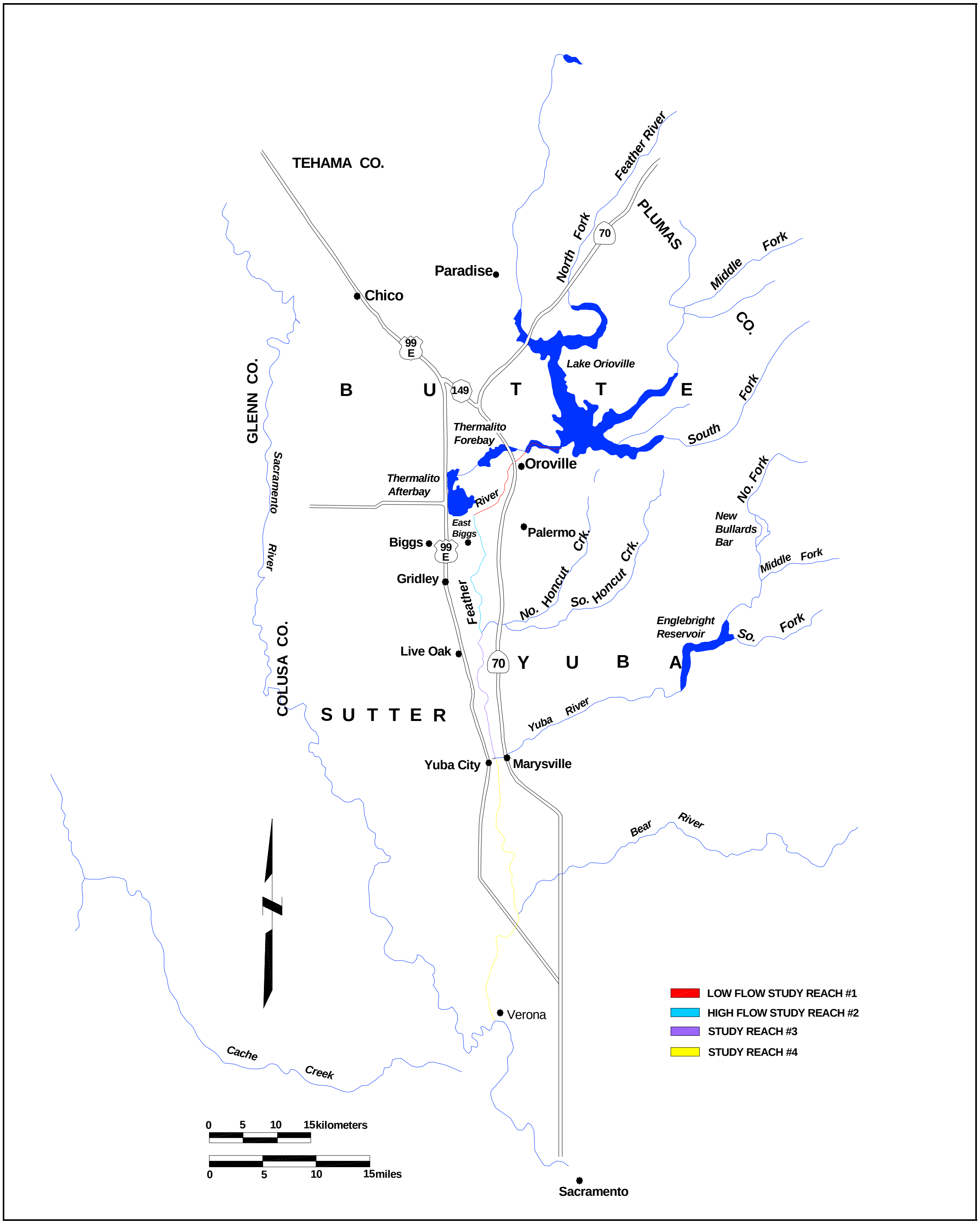

Figure 1.1-1 SP-G2 Geomorphic Study Area and Subreaches, Lake Oroville to Verona.

1.2 DESCRIPTION OF FACILITIES

The Oroville Facilities were developed as part of the State Water Project (SWP), a water storage and delivery system of reservoirs, aqueducts, power plants, and pumping plants. The main purpose of the SWP is to store and distribute water to supplement the needs of urban and agricultural water users in northern California, the San Francisco Bay area, the San Joaquin Valley, and southern California. The Oroville Facilities are also operated for flood management, power generation, to improve water quality in the Delta, provide recreation, and enhance fish and wildlife.

FERC Project No. 2100 encompasses 41,100 acres and includes Oroville Dam and Reservoir, three power plants (Hyatt Pumping-Generating Plant, Thermalito Diversion Dam Power Plant, and Thermalito Pumping-Generating Plant), Thermalito Diversion Dam, the Feather River Fish Hatchery and Fish Barrier Dam, Thermalito Power Canal, Oroville Wildlife Area (OWA), Thermalito Forebay and Forebay Dam, Thermalito Afterbay and Afterbay Dam, and transmission lines, as well as a number of recreational facilities. Figure 1.2-1 shows an overview of these facilities and the FERC Project boundary. Oroville Dam, along with two small saddle dams, impounds Lake Oroville, a 3.5-million-acre-feet (maf) capacity storage reservoir with a surface area of 15,810 acres at its normal maximum operating level.

The hydroelectric facilities have a combined licensed generating capacity of approximately 762 megawatts (MW). The Hyatt Pumping-Generating Plant is the largest of the three power plants with a capacity of 645 MW. Water from the six-unit underground power plant (three conventional generating and three pumping-generating units) is discharged through two tunnels into the Feather River just downstream of Oroville Dam. The plant has a generating and pumping flow capacity of 16,950 cfs and 5,610 cfs, respectively. Other generation facilities include the 3-MW Thermalito Diversion Dam Power Plant and the 114-MW Thermalito Pumping-Generating Plant.

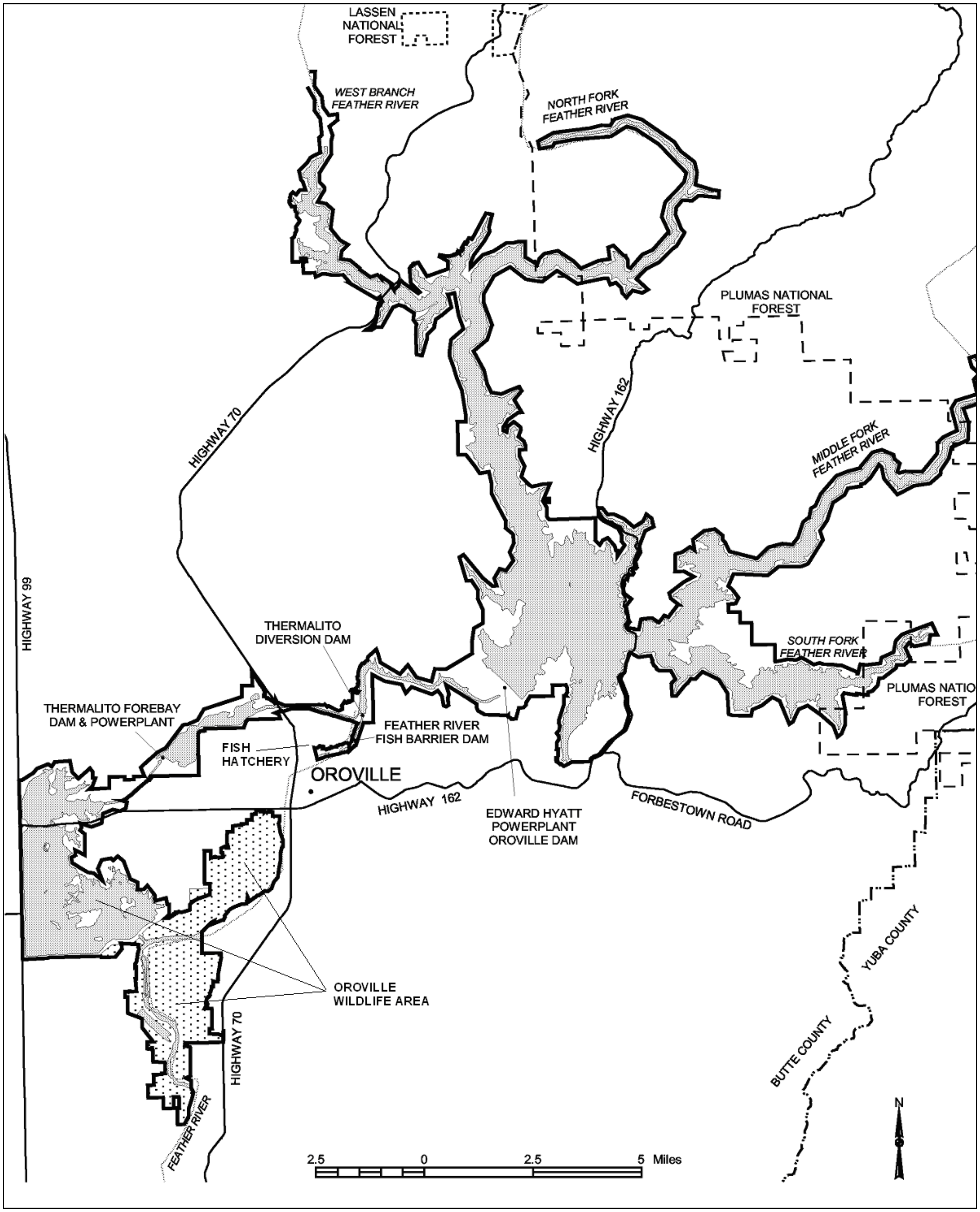

Figure 1.2-1. Overview of FERC Project No. 2100 Facilities.

Thermalito Diversion Dam four miles downstream of the Oroville Dam creates a tail water pool for the Hyatt Pumping-Generating Plant and is used to divert water to the Thermalito Power Canal. The Thermalito Diversion Dam Power Plant is a 3-MW power plant located on the left abutment of the Diversion Dam. The power plant releases a maximum of 615 cubic feet per second (cfs) of water into the river.

The Power Canal is a 10,000-foot-long channel designed to convey generating flows of 16,900 cfs to the Thermalito Forebay and pump-back flows to the Hyatt Pumping-Generating Plant. The Thermalito Forebay is an off-stream regulating reservoir for the 114-MW Thermalito Pumping-Generating Plant. The Thermalito Pumping-Generating Plant is designed to operate in tandem with the Hyatt Pumping-Generating Plant and has generating and pump-back flow capacities of 17,400 cfs and 9,120 cfs, respectively. When in generating mode, the Thermalito Pumping-Generating Plant discharges into the Thermalito Afterbay, which is contained by a 42,000-foot-long earth-fill dam. The Afterbay is used to release water into the Feather River downstream of the Oroville Facilities, helps regulate the power system, provides storage for pump-back operations, and provides recreational opportunities. Several local irrigation districts receive water from the Afterbay.

The Feather River Fish Barrier Dam is downstream of the Thermalito Diversion Dam and immediately upstream of the Feather River Fish Hatchery. The flow over the dam maintains fish habitat in the low-flow channel of the Feather River between the dam and the Afterbay outlet, and provides attraction flow for the hatchery. The hatchery was intended to compensate for spawning grounds lost to returning salmon and steelhead trout from the construction of Oroville Dam. The hatchery can accommodate 15,000 to 20,000 adult fish annually.

The Oroville Facilities support a wide variety of recreational opportunities. They include: boating (several types), fishing (several types), fully developed and primitive camping (including boat-in and floating sites), picnicking, swimming, horseback riding, hiking, off-road bicycle riding, wildlife watching, hunting, and visitor information sites with cultural and informational displays about the developed facilities and the natural environment. There are major recreation facilities at Loafer Creek, Bidwell Canyon, the Spillway, North and South Thermalito Forebay, and Lime Saddle. Lake Oroville has two full-service marinas, five car-top boat launch ramps, ten floating campsites, and seven dispersed floating toilets. There are also recreation facilities at the Visitor Center and the OWA.

The OWA comprises approximately 11,000 acres west of Oroville that is managed for wildlife habitat and recreational activities. It includes the Thermalito Afterbay and surrounding lands (approximately 6,000 acres) along with 5,000 acres adjoining the Feather River. The 5,000 acre area straddles 12 miles of the Feather River, which includes willow and cottonwood lined ponds, islands, and channels. Recreation areas include dispersed recreation (hunting, fishing, and bird watching), plus recreation at developed sites, including Monument Hill day use area, model airplane grounds, three boat launches on the Afterbay and two on the river, and two primitive camping areas. California Department of Fish and Game’s (DFG) habitat enhancement program includes a wood duck nest-box program and dry land farming for nesting cover and improved wildlife forage. Limited gravel extraction also occurs in a number of locations.

1.3 CURRENT OPERATIONAL CONSTRAINTS

Operation of the Oroville Facilities varies seasonally, weekly and hourly, depending on hydrology and the objectives DWR is trying to meet. Typically, releases to the Feather River are managed to conserve water while meeting a variety of water delivery requirements, including flow, temperature, fisheries, recreation, diversion and water quality. Lake Oroville stores winter and spring runoff for release to the Feather River as necessary for project purposes. Meeting the water supply objectives of the SWP has always been the primary consideration for determining Oroville Facilities operation (within the regulatory constraints specified for flood control, in-stream fisheries, and downstream uses). Power production is scheduled within the boundaries specified by the water operations criteria noted above. Annual operations planning are conducted for multi-year carry over. The current methodology is to retain half of the Lake Oroville storage above a specific level for subsequent years. Currently, that level has been established at 1,000,000 acre-feet (af); however, this does not limit draw down of the reservoir below that level. If hydrologic conditions are drier than expected or water requirements greater than expected, additional water would be released from Lake Oroville. The operations plan is updated regularly to reflect changes in hydrology and downstream operations. Typically, Lake Oroville is filled to its maximum annual level of up to 900 feet above mean sea level (msl) in June and then can be lowered as necessary to meet downstream requirements, to its minimum level in December or January. During drier years, the lake may be drawn down more and may not fill to the desired levels the following spring. Project operations are directly constrained by downstream operational constraints and flood management criteria as described below.

1.3.1 Downstream Operation

An August 1983 agreement between DWR and DFG entitled, “Agreement Concerning the Operation of the Oroville Division of the State Water Project for Management of Fish and Wildlife,” sets criteria and objectives for flow and temperatures in the low flow channel and the reach of the Feather River between Thermalito Afterbay and Verona. This agreement: (1) establishes minimum flows between Thermalito Afterbay Outlet and Verona which vary by water year type; (2) requires flow changes under 2,500 cfs to be reduced by no more than 200 cfs during any 24-hour period, except for flood management, failures, etc.; (3) requires flow stability during the peak of the fall-run Chinook spawning season; and (4) sets an objective of suitable temperature conditions during the fall months for salmon and during the later spring/summer for shad and striped bass.

1.3.1.1 Instream Flow Requirements

The Oroville Facilities are operated to meet minimum flows in the Lower Feather River as established by the 1983 agreement (see above). The agreement specifies that Oroville Facilities release a minimum of 600 cfs into the Feather River from the Thermalito Diversion

Dam for fisheries purposes. This is the total volume of flows from the diversion dam outlet, diversion dam power plant, and the Feather River Fish Hatchery pipeline.

Generally, the instream flow requirements below Thermalito Afterbay are 1,700 cfs from October through March, and 1,000 cfs from April through September. However, if runoff for the previous April through July period is less than 1,942,000 af (i.e., the 1911-1960 mean unimpaired runoff near Oroville), the minimum flow can be reduced to 1,200 cfs from October to February, and 1,000 cfs for March. A maximum flow of 2,500 cfs is maintained from October 15 through November 30 to prevent spawning in overbank areas that might become de-watered.

1.3.1.2 Temperature Requirements

The Diversion Pool provides the water supply for the Feather River Fish Hatchery. The hatchery objectives are 52°F for September, 51°F for October and November, 55°F for December through March, 51°F for April through May 15, 55°F for last half of May, 56°F for June 1-15, 60°F for June 16 through August 15, and 58°F for August 16-31. A temperature range of plus or minus 4°F is allowed for objectives, April through November.

There are several temperature objectives for the Feather River downstream of the Afterbay Outlet. During the fall months, after September 15, the temperatures must be suitable for fall-run Chinook. From May through August, they must be suitable for shad, striped bass, and other warmwater fish.

The National Marine Fisheries Service has also established an explicit criterion for steelhead trout and spring-run Chinook salmon. Memorialized in a biological opinion on the effects of the Central Valley Project and SWP on Central Valley spring-run Chinook and steelhead as a reasonable and prudent measure; DWR is required to control water temperature at Feather River mile 61.6 (Robinson's Riffle in the low-flow channel) from June 1 through September 30. This measure requires water temperatures less than or equal to 65°F on a daily average. The requirement is not intended to preclude pump-back operations at the Oroville Facilities needed to assist the State of California with supplying energy during periods when the California ISO anticipates a Stage 2 or higher alert.

The hatchery and river water temperature objectives sometimes conflict with temperatures desired by agricultural diverters. Under existing agreements, DWR provides water for the Feather River Service Area (FRSA) contractors. The contractors claim a need for warmer water during spring and summer for rice germination and growth (i.e., 65°F from approximately April through mid May, and 59°F during the remainder of the growing season). There is no obligation for DWR to meet the rice water temperature goals. However, to the extent practical, DWR does use its operational flexibility to accommodate the FRSA contractor's temperature goals.

1.3.1.3 Water Diversions

Monthly irrigation diversions of up to 190,000 (July 2002) af are made from the Thermalito Complex during the May through August irrigation season. Total annual entitlement of the Butte and Sutter County agricultural users is approximately 1 maf. After meeting these local demands, flows into the lower Feather River continue into the Sacramento River and into the Sacramento-San Joaquin Delta. In the northwestern portion of the Delta, water is pumped into the North Bay Aqueduct. In the south Delta, water is diverted into Clifton Court Forebay where the water is stored until it is pumped into the California Aqueduct.

1.3.1.4 Water Quality

Flows through the Delta are maintained to meet Bay-Delta water quality standards arising from DWR's water rights permits. These standards are designed to meet several water quality objectives such as salinity, Delta outflow, river flows, and export limits. The purpose of these objectives is to attain the highest water quality, which is reasonable, considering all demands being made on the Bay-Delta waters. In particular, they protect a wide range of fish and wildlife including Chinook salmon, Delta smelt, striped bass, and the habitat of estuarine-dependent species.

1.3.2 Flood Management

The Oroville Facilities are an integral component of the flood management system for the Sacramento Valley. During the wintertime, the Oroville Facilities are operated under flood control requirements specified by the U.S. Army Corps of Engineers (USACE). Under these requirements, Lake Oroville is operated to maintain up to 750,000 af of storage space to allow for the capture of significant inflows. Flood control releases are based on the release schedule in the flood control diagram or the emergency spillway release diagram prepared by the USACE, whichever requires the greater release. Decisions regarding such releases are made in consultation with the USACE.

The flood control requirements are designed for multiple use of reservoir space. During times when flood management space is not required to accomplish flood management objectives, the reservoir space can be used for storing water. From October through March, the maximum allowable storage limit (point at which specific flood release would have to be made) varies from about 2.8 to 3.2 maf to ensure adequate space in Lake Oroville to handle flood flows. The actual encroachment demarcation is based on a wetness index, computed from accumulated basin precipitation. This allows higher levels in the reservoir when the prevailing hydrology is dry while maintaining adequate flood protection. When the wetness index is high in the basin (i.e., wetness in the watershed above Lake Oroville), the flood management space required is at its greatest amount to provide the necessary flood protection. From April through June, the maximum allowable storage limit is increased as the flooding potential decreases, which allows capture of the higher spring flows for use later in the year. During September, the maximum allowable storage decreases again to prepare for the next flood season. During flood events, actual storage may encroach into the flood reservation zone to prevent or minimize downstream flooding along the Feather River.

2.0 NEED FOR STUDY

2.1 PURPOSE AND SCOPE

A naturally functioning channel in dynamic equilibrium is capable of transporting the water and sediment delivered to it without significantly changing its geometry, streambed composition, or gradient through time. The flow conditions that promote this stability can be described as geomorphically significant flows (bankfull). These flows do the majority of the sediment transport and are considered most responsible for channel form. A natural flow regime typically includes flow ranges responsible for in-channel clearing and overbank flows to support riparian vegetation, along with channel-forming flows.

The altered sediment routing and hydrology caused by the Oroville Facilities have affected river morphology. There is a need to understand these relationships and identify potential protection, mitigation and enhancement measures.

The SP-G2 Task 5 Report compares historic and current conditions to identify ongoing project effects to the downstream reach defined in this study. This information will be used to identify continuing project effects to downstream geomorphologic processes. It will also be used by other studies to help assess the project's effects on plant, fish, animal, and riparian resources caused by hydrologic, channel, and sediment routing changes. These data, together with other study results, will provide boundary conditions for assessing potential management actions.

Project related structures and operations also alter the flow regime, affecting the occurrence of geomorphically significant flows. The report defines these flow conditions and addresses potential adverse effects from these flows including loss of undercut banks, increased instream fine sediment, braiding, loss of channel capacity, reduced sediment transport capability, gravel displacement, unnatural channel scour, armoring, and impairment of the ability of the stream to maintain functional riparian and instream habitat. Project-related structures and operations can also impair the stream's ability to transport the sediment delivered to it from source areas.

3.0 STUDY OBJECTIVE(S)

3.1 APPLICATION OF STUDY INFORMATION

The objective is to determine the ongoing effects of altered downstream hydrology and sediment retention in Lake Oroville on channel morphology and sediment transport below Lake Oroville.

The study will determine the ongoing Oroville Project effects on river flows and morphology downstream of Oroville Dam. Specifically, the study will address the following components:

1. Determine sediment conditions and sediment transport requirements.
2. Evaluate sediment sources (including tributaries) and conditions.
3. Map major sediment deposits.
4. Evaluate stream channel stability.
5. Evaluate project-affected sediment regimes.
6. Evaluate timing, magnitude, and duration of project-affected flows in relation to geomorphic effects.
7. Determine the effect of the project on fluvial geomorphologic features.
8. Evaluate erosional effects on farmland and public trust resources.

Study results may be used to identify limiting factors and biological effects. The information could be used to develop a comprehensive sediment and flow regime management plan to improve form and function in the Feather River. The study results could also be used by other studies to help assess the Oroville Facilities ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources.

3.2 OTHER STUDIES

Studies related to spawning gravel quantity and quality began before construction of Oroville Dam. DWR (1965) studied pre-dam channel characteristics, and then DWR (1969) and the USGS (1972) conducted studies to document channel changes. In 1977 DFG studied the interim impacts of the dam on salmonid escapement. In 1978 the USGS completed a study to evaluate sediment transport and discharge.

DWR (1982) prepared the Feather River Spawning Gravel Baseline Study to determine post dam spawning gravel conditions. The report presented spawning gravel sampling results and identified factors resulting in loss of spawning gravel quality. These include the lack of gravel recruitment from areas above Oroville Dam and the effect of scouring flood flows. A follow-up habitat restoration project was conducted by DWR and DFG in 1982 at the riffle sites adjacent to the Hatchery. These sites were identified in the baseline study as having undergone significant post-dam degradation.

Additional information on other studies is included in the Task 1.1 report.

4.0 STUDY ORGANIZATION

4.1 STUDY DESIGN

It is widely recognized that dams affect downstream reaches of the river system in significant ways. These reaches experience departures from natural conditions by changes in their water yield, flows, low flows, and timing of discharge events as well as sediment discharge and the size distribution of sediment. This in turn affects the geomorphology, riparian vegetation, fish and wildlife. These characteristics interact so as to approach a state of dynamic equilibrium. The alteration of any one of the characteristics will disrupt the equilibrium, forcing readjustment of the other variables toward a new altered state of equilibrium. This report examines river hydraulics and geomorphology. Effects on biotic systems are addressed by other study plans.

4.2 HOW AND WHERE THE STUDIES WERE CONDUCTED

The first half of the Task 5 Report focused on collecting existing survey, topographic, and photographic data. It also plotted channel locations for the years available on the atlas and the GIS. Changes in channel location, islands, multiple channel areas, levees, and riprap were delineated. Ongoing impacts of the dam were evaluated by comparing pre- and post dam bank erosion and channel migration rates, island and multiple channel formation rates, gravel bars, riffles, channel width, gradient, and other geomorphic characteristics. Figures, graphs, and charts were prepared and presented showing the changes.

The second half of the report focused on determining the effect of project operations on channel geomorphology. This was done by using geologic maps in conjunction with aerial photo interpretation to identify structural controls on river erosion and plan form. These aerial photos and old survey maps were used to establish the location of historic river channels and used to establish the extents of the meander belt. Available past cross-sectional data was also compared to those surveyed in Task 3 to determine changes in channel shape, form, and function caused by the dam. Finally changes in depth, width, hydraulic radius, roughness, gradient, pool-riffle-run ratio, and other hydraulic parameters were determined.

5.0 PROJECT EFFECTS ON DOWNSTREAM RIVER HYDRAULICS

River hydraulics are the characteristics of streamflow such as discharge, peak, yearly average, velocity, depth, monthly average, and flow timing. Dams affect the streamflow by storing and releasing water on a schedule that generally differs from the natural flow regimen. The degree of change defines the amount of hydraulic alteration. This study evaluated Project effects by comparing pre- and post Oroville Dam flow conditions.

Pre-dam flows for the hydraulic analyses were defined as available gaging station data prior to November 1967. Oroville Dam was completed in that year, although some minor flow modification occurred prior to that as a result of construction activities.

Post dam conditions are defined by available gaging station data from November 1967 to present.

The Feather River was divided into hydrologic reaches defined by available gaging stations and by location of tributaries. The following are the reaches used for this study:

- The Fish Barrier Dam to Thermalito Afterbay Outfall Reach. This is referred to as the Low Flow Reach and is upstream of the Thermalito Afterbay discharge to the Feather River. The Feather River at Oroville gage defines the flow.
- Thermalito Afterbay Outfall to Yuba City Reach. This is referred to as the High Flow Reach. The Feather River near Gridley gage, and/or the combination of the Feather River at Oroville with the Thermalito Afterbay Outfall. The Feather River at Yuba City provides the flow at the lower end of this reach. Honcut Creek is the only significant tributary, but the flow contribution is small.
- Yuba City to Verona Reach. The Yuba River enters the Feather at the upstream end of the reach. A combination of the Feather River at Yuba City and the Yuba River at Yuba City gages defines the flow at the upstream end of the reach. The smaller Bear River enters the Feather above the town of Nicolaus. The Feather River near Nicolaus gage was used to define the flow for the lower part of the reach.

Hydraulic changes to the Low Flow Reach and the High Flow Reach are discussed here. These are the two reaches most affected by the Project. Hydraulic changes to the Yuba City to Verona Reach are complicated by dams on the Yuba and Bear Rivers. The hydrology of this reach was discussed in the Task 1.2 Report.

Two types of hydraulic analyses were done. The first analysis included preparation of graphs and tables for the Feather River at Oroville and the Feather River near Gridley gages, showing changes in average yearly flow, monthly flow, peak flow, flow exceedance, and flood frequency. The second included preparation of an “Indicators of Hydraulic Alteration” analysis, a program developed by The Nature Conservancy. The IHA analysis is particularly useful for determining the degree of hydraulic alteration caused by dams. The IHA analysis is published separately as Appendix A to this report.

It is important to note that many of the changes in hydrology are not a result of the Oroville Project. This is discussed in detail in the Task 1.2 Report and includes other dams and diversions, levees, dredging, timber harvesting, grazing, mining activities, urbanization, and agriculture. Most of these changes occurred prior to construction of the Oroville Facilities.

5.1 CHANGES IN HYDRAULIC PARAMETERS

Gaging stations useful for geomorphic analyses of the lower Feather River are shown in Table 5.1-1. Note that for some of the gages the pre-dam records are short. The Feather River at Oroville has the longest record. The “at Oroville” and “near Gridley” gages are the most significant for evaluating hydraulic changes caused by the Oroville Facilities.

Table 5.1-1 Gaging Stations for the Feather River below Lake Oroville.

GAGE NAME	NUMBER	PERIOD OF RECORD	MEAN FLOW CFS		AREA SQ. MI
			PRE-PROJECT	POST	
Lake Oroville near Oroville	11406800	Nov. 1967 -	--		3,607
Sum of diversions	na	Nov. 1967 -	---	1,080	na
Feather River at Oroville	11407000	Oct. 1901 -	6,280*	1140	3,624
Feather River near Gridley	11407150	Oct 1964 -	-----	4,852	3,676
Feather River at Yuba City	11407700	Oct 1964 -1984	----	6,131	3,974
Feather River near Nicolaus	11425000	Apr. 1942 - 1983	7,863	8,762	5,921

* Adjusted yield for evaporation from Lake Oroville and diversions, 1902 - 2000. Annual yield from 1902 to 1967 is 5830 cfs; from 1967 to 2000 is 1140 cfs.

5.1.2 Feather River at Oroville

The Feather River at Oroville gage is downstream of the Thermalito Diversion Dam. From 1901 to 1967, the gage recorded flows characteristic of pre - dam conditions. The annual mean flow was 5,830 cfs. After 1967, much of the flow was diverted by the Thermalito Diversion Dam to the Thermalito Forebay and Thermalito Afterbay. During most of the year, flows averaging between 500 and 600 cfs occur in the Low Flow Reach of the river between the Thermalito Diversion Dam and the Thermalito Afterbay discharge to the Feather River. The annual mean flow is 1,140 cfs using 1967 to 2000 water years.

The pre - and post Oroville Dam mean monthly streamflow is shown Figure 5.1-1. All 12 months are affected significantly, but the spring snowmelt months have the largest changes.

Figure 5.1-2 shows the flow exceedance for the Feather River at Oroville gage. The flow exceeded 99 percent of the time decreased from 950 cfs to 300 cfs from pre- to post dam. The 90 percent exceedance flow decreased from 1,400 cfs to about 300 cfs, and the 50 percent exceedance flow decreased from 3,000 cfs to 350. The flow exceeded one percent of the time changed from 37,000 to 21,000 cfs.

Figure 5.1-3 shows the pre- and post project flood frequency curves. The 2 year recurrence interval flood decreased from 65,000 to 3,000. The 10 year recurrence event decreased from 160,000 to 75,000. The 50 year event decreased from 240,000 to 180,000 cfs.

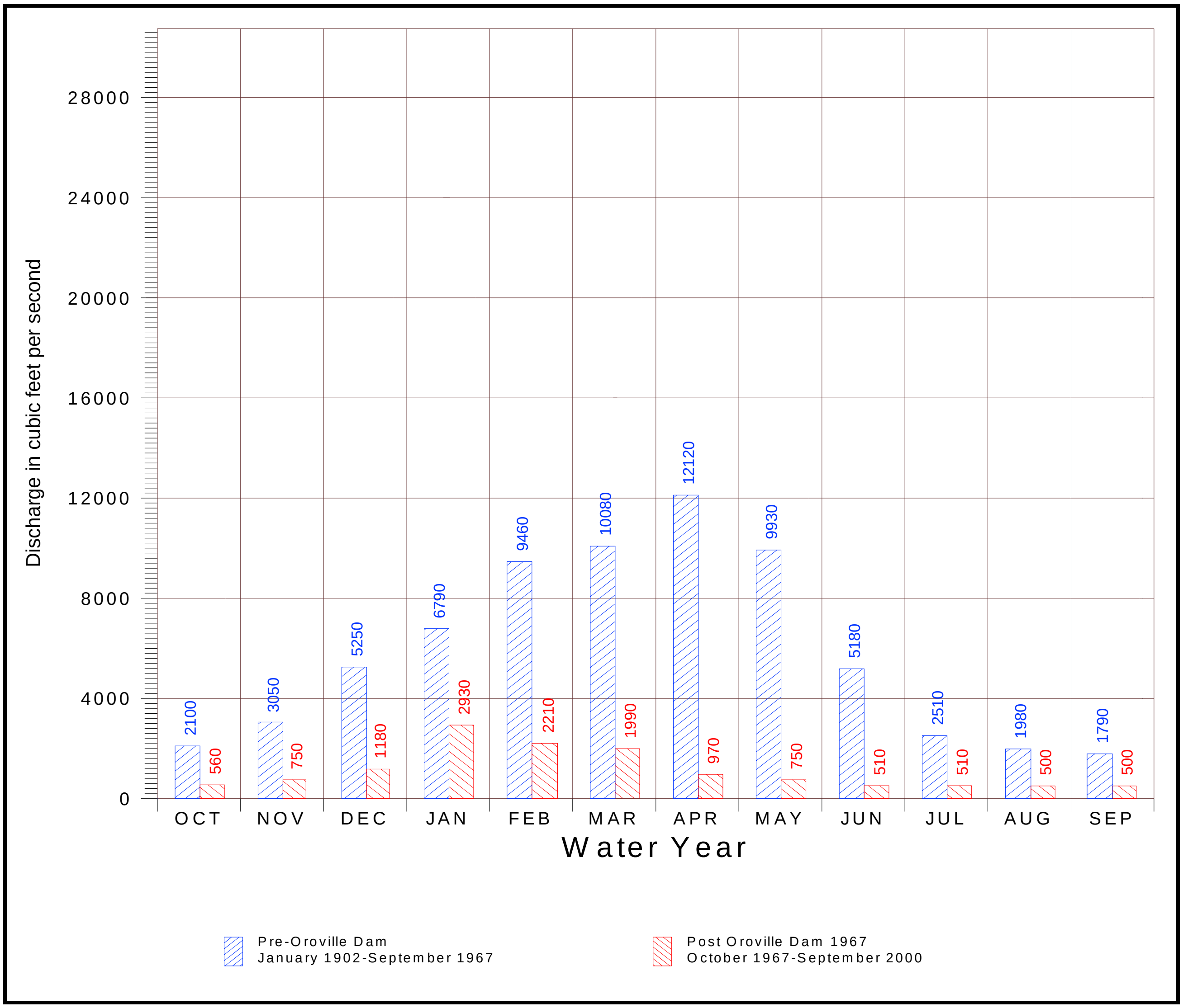

Figure 5.1-1 Feather River at Oroville Mean Monthly Flow Data.

There are five diversions from Lake Oroville and Thermalito Afterbay. These are the Palermo Canal (11406810) with an annual mean flow of 10.5 cfs, the Western Canal (11406880) with an average annual mean flow of 320 cfs, the Richvale Canal (11406890) with a flow of 127 cfs, the Pacific Gas and Electric Co. lateral Intake with a flow of 644 cfs. The average combined annual diversion from these is about 1,100 cfs. This is about 20 percent of the average annual yield of the Feather River at this point. July has the highest diversion, with the combined diversion averaging 2,600 cfs (1967-98). The diversions affect the streamflow for all the Feather River gages used in the study.

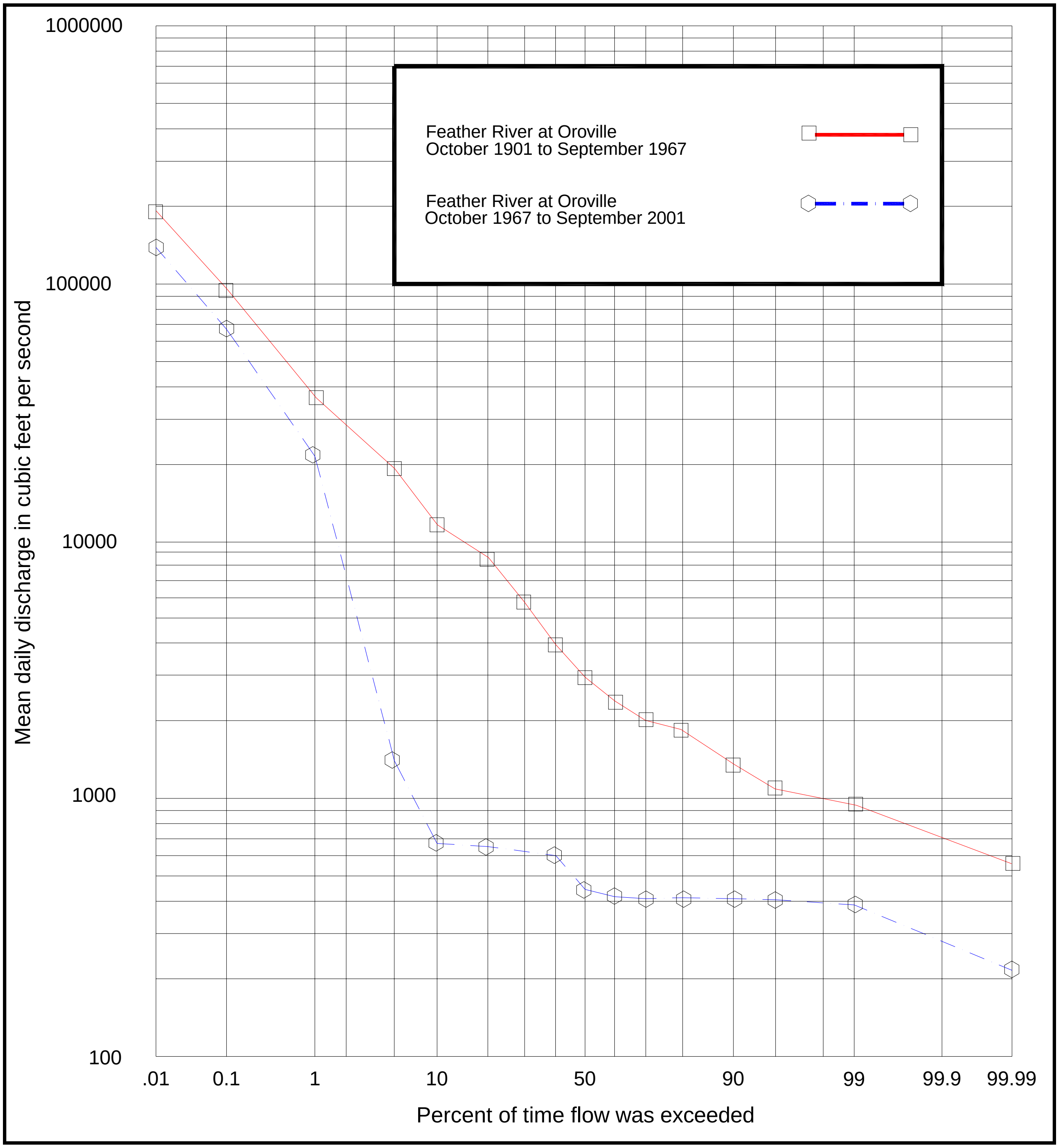

Figure 5.1-2 Feather River at Oroville Flow Exceedance Graph.

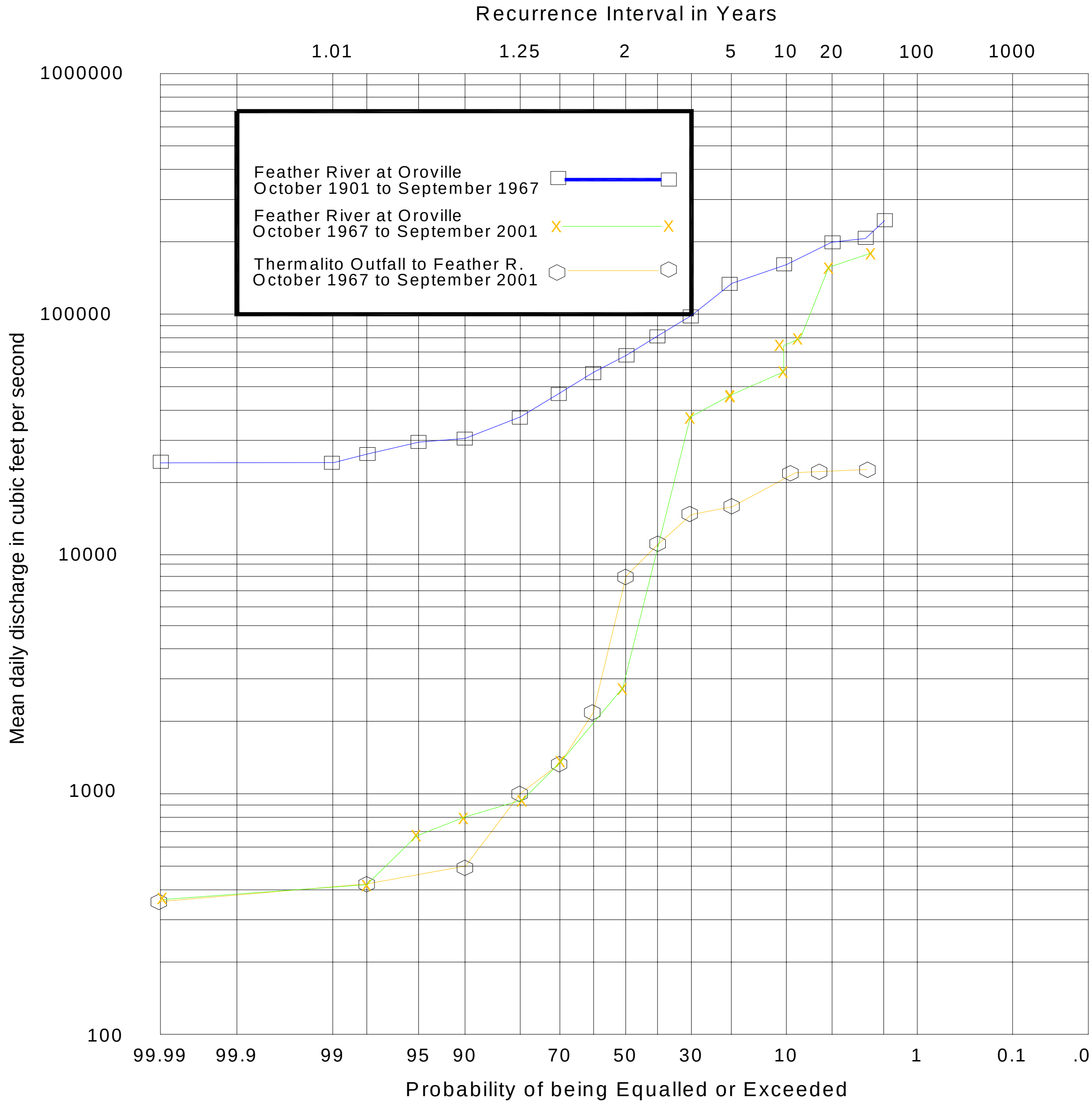

Figure 5.1-3 Feather River at Oroville Flood Frequency Graph.

Figure 5.1-4, derived from the U.S. Geological Survey website, shows a graph of the peak daily flood flows for the gage. Note that since 1967, there are many years when the minimum release to the Low Flow Reach is also the mean annual flood.

Table 5.1-2 shows the peak daily flow for flood years. Years without flood flows are not shown.

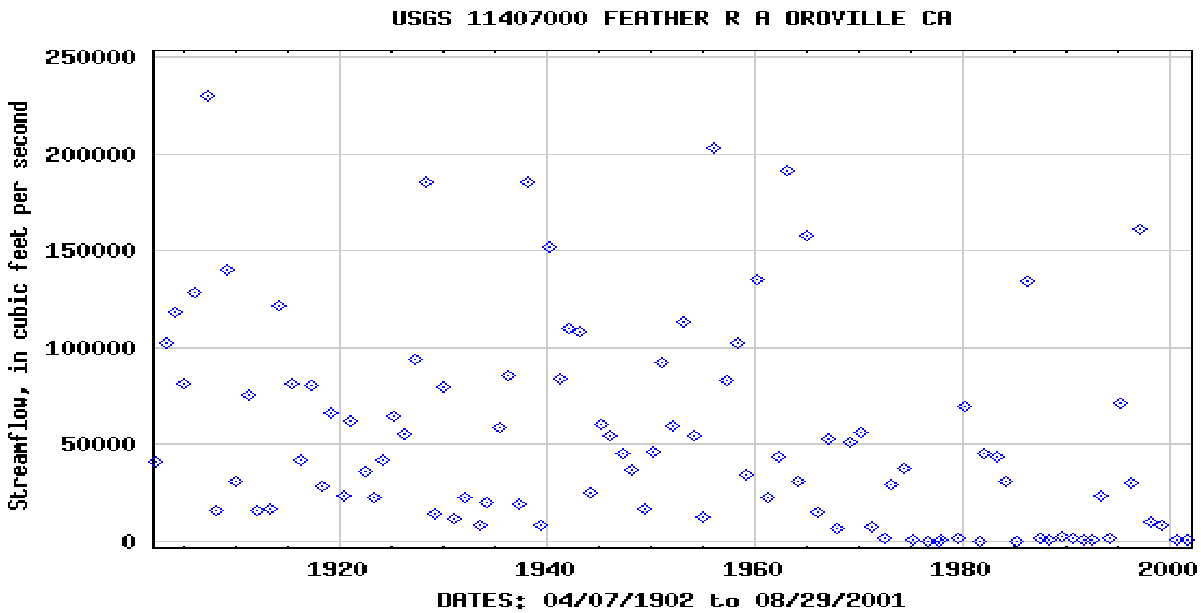

Figure 5.1-4 Peak Flows for the Feather River at Oroville Gage.

Table 5.1-2 shows the available peak flows for the Feather River gaging stations.

Table 5.1-2 Peak Flows for Feather River Gaging Stations.

	CALENDAR YEAR	Oroville * 11407000 (1,000 cfs)	Gridley 11407150 (1,000 cfs)	Yuba City 11407700 (1,000 cfs)	Olivehurst 11421700 (1,000 cfs)	Nicolaus 11425000 (1,000 cfs)
- - Pre - Oroville Dam Peak Flow Events - -	1903	102	- - -	- - -	- - -	- - -
	1904	118	- - -	- - -	- - -	- - -
	1906	128	- - -	- - -	- - -	- - -
	1907	230	- - -	- - -	- - -	- - -
	1909	140	- - -	- - -	- - -	- - -
	1913	122	- - -	- - -	- - -	- - -
	1928	185	- - -	- - -	- - -	- - -
	1937	185	- - -	- - -	- - -	- - -
	1940	152	- - -	- - -	- - -	- - -
	1942	110	- - -	- - -	- - -	- - -
	1943	108	- - -	- - -	- - -	- - -
	1953	113	- - -	- - -	- - -	127
	1955	203	- - -	- - -	- - -	357
	1958	102	- - -	- - -	- - -	- - -
	1960	135	- - -	- - -	- - -	136
	1963	191	- - -	- - -	- - -	264

CALENDAR YEAR	Oroville * 11407000 (1,000 cfs)	Gridley 11407150 (1,000 cfs)	Yuba City 11407700 (1,000 cfs)	Olivehurst 11421700 (1,000 cfs)	Nicolaus 11425000 (1,000 cfs)
1964	158	151	182	- - -	281

* 1901 - 1967: Pre - Oroville Project minimum flood flow recorded in table is 100,000 cfs
* * flood event referenced in text
\- - - means no available data

Post - Oroville Dam Peak Flow - - - - - Events

CALENDAR YEAR	Oroville * 11407000 (1,000 cfs)	Gridley 11407150 (1,000 cfs)	Yuba City 11407700 (1,000 cfs)	Olivehurst 11421700 (1,000 cfs)	Nicolaus 11425000 (1,000 cfs)
1967	53.3	45.6	52.8	- - -	96.6
1969	51.1	56.4	48.1	- - -	88.4
1970	56.3	72.9	74.5	133	146
1973	29.7	47	54.6	62.1	72
1974	37.8	54.7	55.3	88	108
1980	69.5	90.1	- - -	105	115
1981	45	61.8	- - -	- - -	148
1983	43.5	60	- - -	- - -	112
1986	134	150	- - -	- - -	- - -
1993	23.4	37.7	- - -	- - -	- - -
1995	71.7	89.4	- - -	- - -	- - -
1996	30.2	45.7	- - -	- - -	- - -
1997	161	163	- - -	- - -	- - -
1998	10.2	26.4	- - -	- - -	- - -

* 1967 - Post Oroville Project minimum flood flow recorded is 10,000 cfs
\- - - no available data

5.1.3 Feather River at Gridley Gage

The Feather River near Gridley gage is about 300 feet upstream of the East Gridley Road bridge and three miles east of Gridley. The Gridley station best represents flows in the Feather River in the High Flow Reach between the Thermalito outfall and the mouth of Honcut Creek. The record begins in 1964 and ends in 1998. No tributaries occur between the Oroville gage and Gridley, but the station reflects diversions made upstream. The three years of pre-dam record is not sufficient to make significant conclusions regarding changes, so the pre-dam data from the “at Oroville” gage was used.

Figure 5.1-5 shows the mean monthly sum of diversions from the Oroville project above the Gridley gage. July is the month with the largest mean monthly diversion, with an average flow of 2,600 cfs.

The pre - and post dam changes in mean monthly discharge is shown in Figure 5.1-6. The largest mean monthly change occurs in April with a drop from 12,120 to 6,800 cfs. The largest increase in streamflow occurs in August, from 1,980 to 3,810 cfs.

Figure 5.1-6 shows the flow exceedance for the period of record for the Gridley gage. Compare this with the pre-dam graph from the “at Oroville” gage to see the change in exceedance.

Figure 5.1-8 shows the flood frequency for the period of record. Compare this with the pre-dam graph from the ‘at Oroville” gage to see the changes.

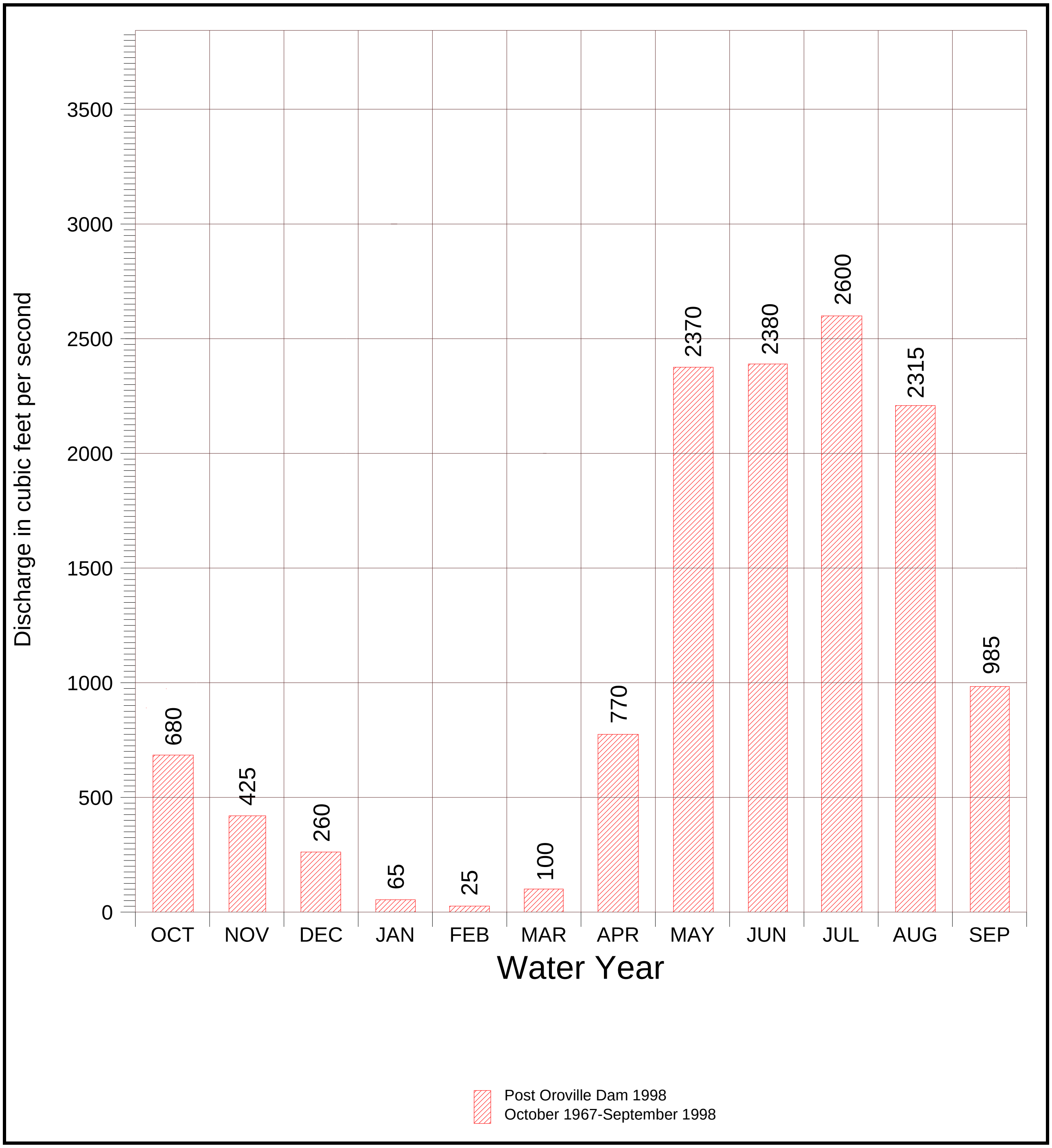

Figure 5.1-5 Sum of Mean Monthly Diversions from Lake Oroville and the Thermalito Afterbay.

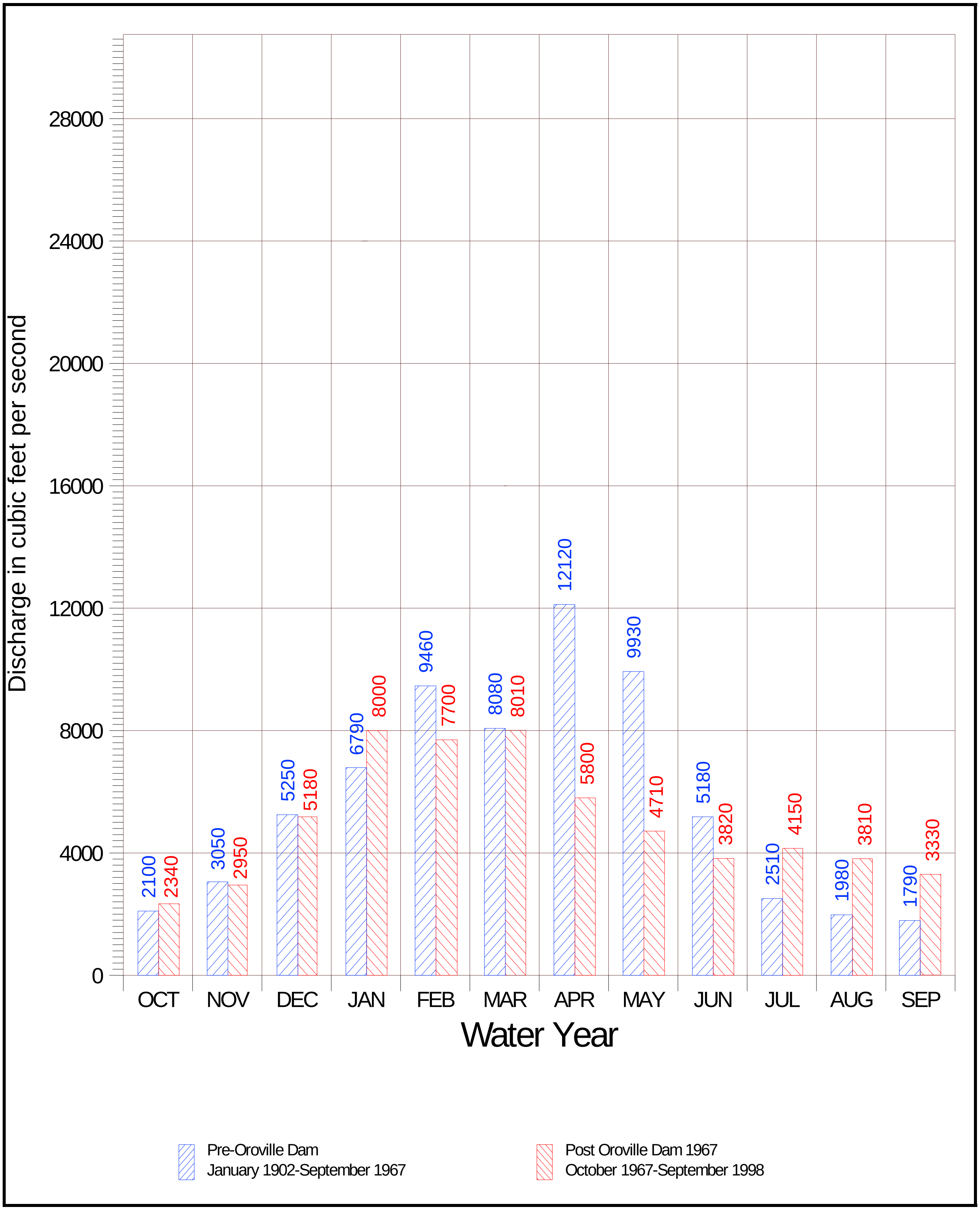

Figure 5.1-6 Feather River near Gridley Changes in Mean Monthly Discharge.

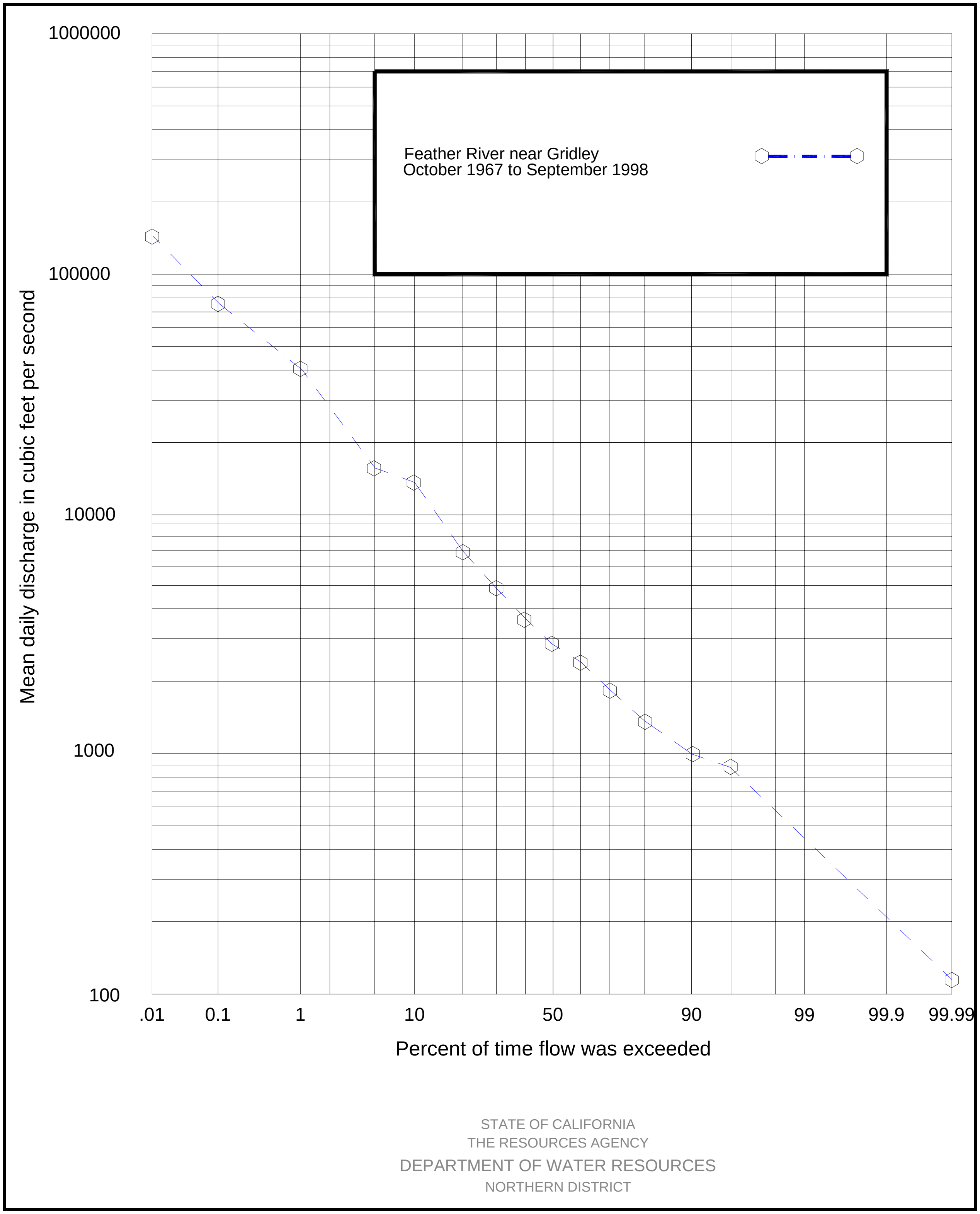

Figure 5.1-7 Feather River near Gridley Flow Exceedance.

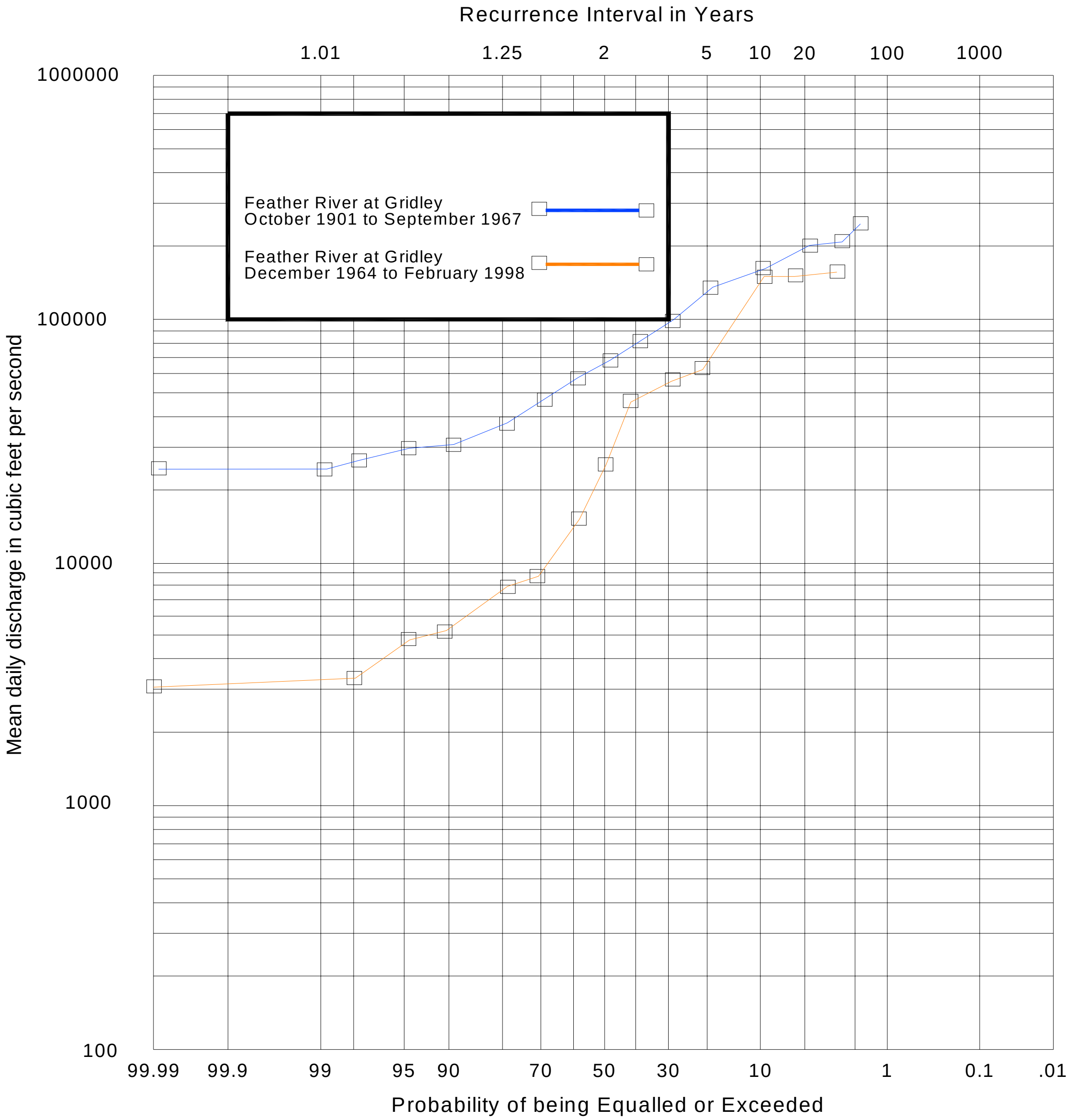

Figure 5.1-8 Feather River near Gridley Flood Frequency.

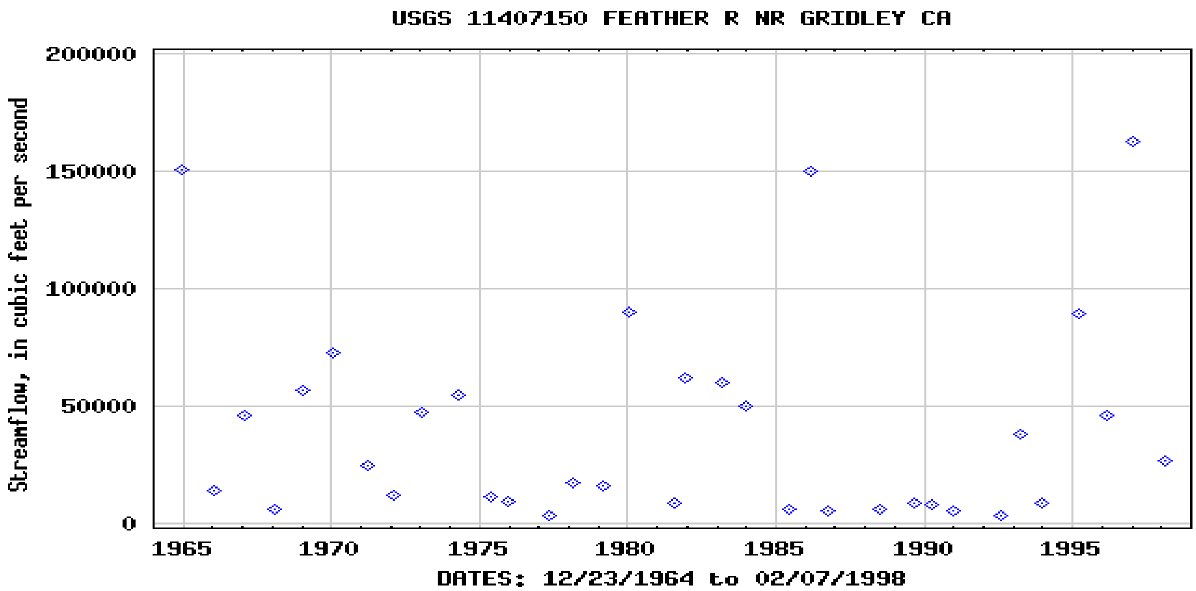

Figure 5.1-9 Post dam Peak Flows for the Feather River near Gridley Gage.

5.2 INDICATORS OF HYDRAULIC ALTERATION ANALYSIS

The Indicators of Hydraulic Alteration analysis, or IHA, is a tool for calculating hydrologic regime characteristics and changes. The program calculates long-term changes over time and can calculate the degree of change caused by such features as dams and diversions. IHA is a statistical analysis methodology that provides numerical and graphic outputs showing the degree and type of hydrologic changes using standard, accepted statistical tools. The program was developed by The Nature Conservancy (2001).

The purpose of the analysis is to evaluate potential hydrologic alteration to the Feather River due to operations associated with Oroville Dam. The completion of Oroville Dam in 1967 divides the hydrologic record into two distinct hydrologic periods. The pre-dam hydrologic period includes streamflow data available at a gage prior to November 1967. The post dam hydrologic period extends from November 1967 to the present.

DWR used the IHA to evaluate pre- and post dam hydraulic changes using three gaging stations. These are the Feather River at Oroville (USGS 11407000), the Thermalito Afterbay release to Feather River, near Oroville (USGS 11406920) and the Feather River at Nicolaus (USGS 11425000). These are shown in Figure 5.2-1. The IHA report, with full analyses, graphs, charts, and explanations, is in the Appendix. A summary of the findings is presented here.

The gages are downstream of Oroville Dam but were affected to different degrees. The Oroville gage represents pre-dam conditions from Oroville to Yuba City, and post dam flow conditions in the Low Flow Reach between Oroville and the Thermalito Afterbay Outfall release to the Feather River.

The Thermalito Afterbay release was combined with the Feather River at Oroville gage discharge to approximate the post Oroville Dam hydrologic period in the High Flow Reach downstream to Yuba City. The Nicolaus gage was used to characterize the reach between Yuba City and Verona and includes the flow from the Yuba and Bear rivers. Other gaging stations were not used because of a limited record or lack of data spanning the pre- and post dam period.

The program uses for the analysis mean daily flow records from the U.S. Geological Survey, or from other sources. The program then converts this information into a set of 33 readily understandable, ecologically and functionally relevant hydrologic parameters. These are in Table 5.2-1.

The program may also be used to implement a Range of Variability Approach (RVA). The RVA was used by DWR in this analysis since this approach is particularly effective where dams and diversions have caused changes. The RVA defines the pre-dam hydraulic conditions over the period of record and compares them to post dam conditions. A management goal then would be to keep the IHA parameters as close as practical to the pre-impact conditions.

There are two commonly used statistical methods of evaluating the range and variation of a hydrologic variable: parametric and nonparametric. Parametric analysis uses the mean and standard deviation to evaluate the range of a variable, while nonparametric analysis uses percentiles (25th, 50th, and 75th percentiles). Nonparametric is often more suitable because hydrologic data distributions are more J-shaped (bell with one side shortened) than bell-shaped (Richter et. al. 1997, in TNC 2001). This was found to be the case on the Feather River, so while both types were calculated, only the nonparametric was graphed and discussed.

The IHA analysis demonstrates some of the pre- and post project hydrologic changes that have occurred in the Feather River. Table 5.2-2 and the following are examples:
[

- Mean summer flows have been reduced to 23 percent in July and 24 percent in August of the pre-dam flows at Oroville, but increased 580 percent in July and 1,100 percent in August at Nicolaus;

- One-day minimum summer flows reduced to 34 percent at Oroville but increased 475 percent at Nicolaus;

- Mean monthly spring flows reduced to 5 percent for Oroville and 50 percent for Nicolaus; and

- Number of river stage reversals increased 132 percent at Oroville but decreased slightly to 95 percent at Nicolaus.

Table 5.2-1 IHA Hydrologic Parameters.

IHA Statistics Group	Regime Characteristics	Hydrologic Parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean October flow
		Mean November flow
		Mean December flow
		Mean January flow
		Mean February flow
		Mean March flow
		Mean April flow
		Mean May flow
		Mean June flow
		Mean July flow
		Mean August flow
		Mean September flow
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual 1-day mean minimum flow
		Annual 3-day mean minimum flow
		Annual 7-day mean minimum flow
		Annual 30-day mean minimum flow
		Annual 90-day mean minimum flow
		Annual 1-day mean maximum flow
		Annual 3-day mean maximum flow
		Annual 7-day mean maximum flow
		Annual 30-day mean maximum flow
		Annual 90-day mean maximum flow
		Number of zero days
		Base flow (7-day minimum over mean annual flow)
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day minimum
		Julian date of each annual 1-day maximum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses (above 75th percentile) each year
		Number of low pulses (below 25th percentile) each year
		Mean duration of high pulses within each year (days)
		Mean duration of low pulses within each year (days)
Group 5: Rate and frequency of water condition changes	Frequency Rate of Change	Means of all positive differences between consecutive daily values (rise rate)
		Means of all negative differences between consecutive daily values (fall rate)
		Number of reversals

Note that not all the changes can be attributed to the Oroville Project. Englebright Dam on the Yuba, Camp Far West on the Bear River, and numerous other smaller reservoirs on all three rivers, all affect the streamflow to some extent.

The IHA methodology yields the quantity, trends and changes in 33 distinct variables, which measure the magnitude, duration, frequency, timing and rates of change of flows.

Table 5.2-2 Examples of Changes in Feather River Hydrologic Characteristics

Parameter	Oroville Gage Low Flow Reach	Combined Oroville-Thermalito Gages	Nicolaus
Mean June flows	Reduced 90%	Reduced 29%	Increased 21%
Mean July flows	Reduced 81%	Increased 90%	Increased 603%
One-day minimum flows	Reduced 67%	Reduced 2%	Increased 400%
Mean April flows	Reduced 94%	Reduced 77%	Reduced 53%
Number of river stage reversals	Increased 35%	Increased 2%	Reduced 4%

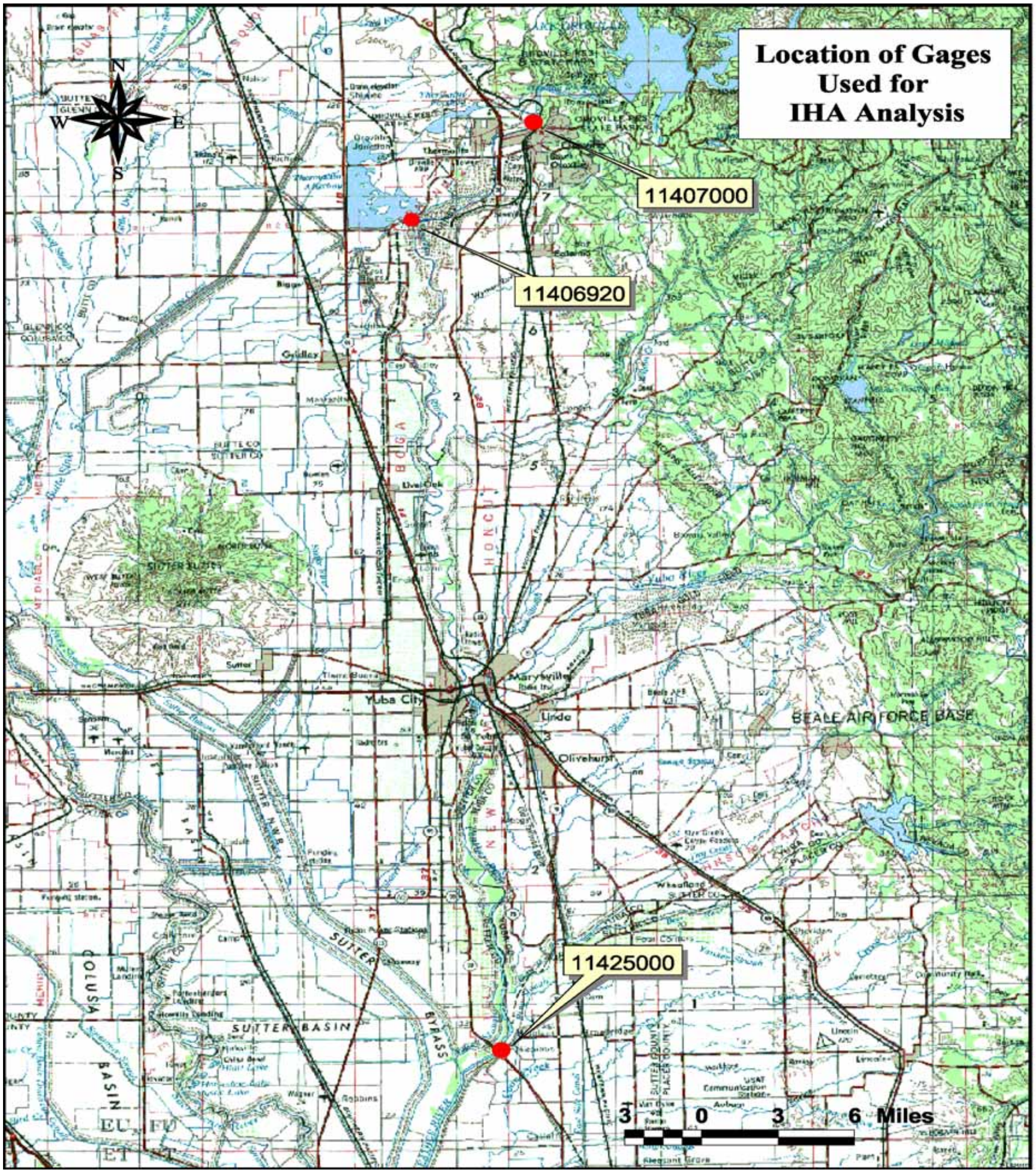

Figure 5.2-1 Location Map of IHA Gages.

5.2.1 Thermalito Diversion Dam to Thermalito Afterbay Reach IHA Analysis

The Feather River at Oroville gage approximately represents the pre-dam reach of the Feather between Oroville and Yuba City. The gage has a long period of record, extending from October 1901 to the present. For post dam conditions, it only

represents the Low Flow Reach between the Thermalito Diversion Dam (RM 68) and the Thermalito Afterbay release to the Feather River (RM 59), a river distance of about nine miles.
[
Figure 5.2-2 shows the alteration in magnitude of the 33 hydrologic parameters for the Feather River near Oroville gage. The alteration has been generalized using the qualifiers low, moderate, and large. Most of the parameters have had a large, but a few have had a moderate or low shift in value. The parameters with a large shift include mean monthly flows, magnitude and duration of extreme discharges, the frequency and duration of high and low pulses, and the frequency of hydrograph changes.

The figure also shows the results for the Oroville gage graphically. Although somewhat difficult to interpret, this figure shows all 33 hydraulic variables. The flows and other hydraulic variables are divided into three sets: those values that fit within historic period Range of Variability Approach range; those that are above historic period RVA range; and those that fit below historic period RVA range. These three ranges are then plotted on the figure according to the degree of hydrologic alteration, with zero corresponding to no hydrologic alteration. Negative values correspond to too few values in the range, and positive values to too many values in the range.

Figure 5.2-3 is an example of IHA nonparametric analysis of mean June flows at the gage. The graph not only shows the yearly variation in the mean June flow for the period of record, but also shows the 25, median, and 75 percentile values. Graphs for the remaining 11 months are in the IHA Appendix.

Summarizing the RVA analysis, the only variable to show no change was the number of zero-flow days. Only one variable, the date of maximum flow, showed low alteration. A large degree of alteration occurred for all 31 remaining variables.

The results show a very large degree of alteration in many of the hydrologic variables. The main reason for this is the flood control and storage aspects of Oroville Dam. In addition, the gage is in the low flow reach. This means that the majority of both the summer and winter flows are diverted around this reach by the Thermalito Diversion Dam. A minimum of about 600 cfs occurs most of the year as a fish maintenance flow.

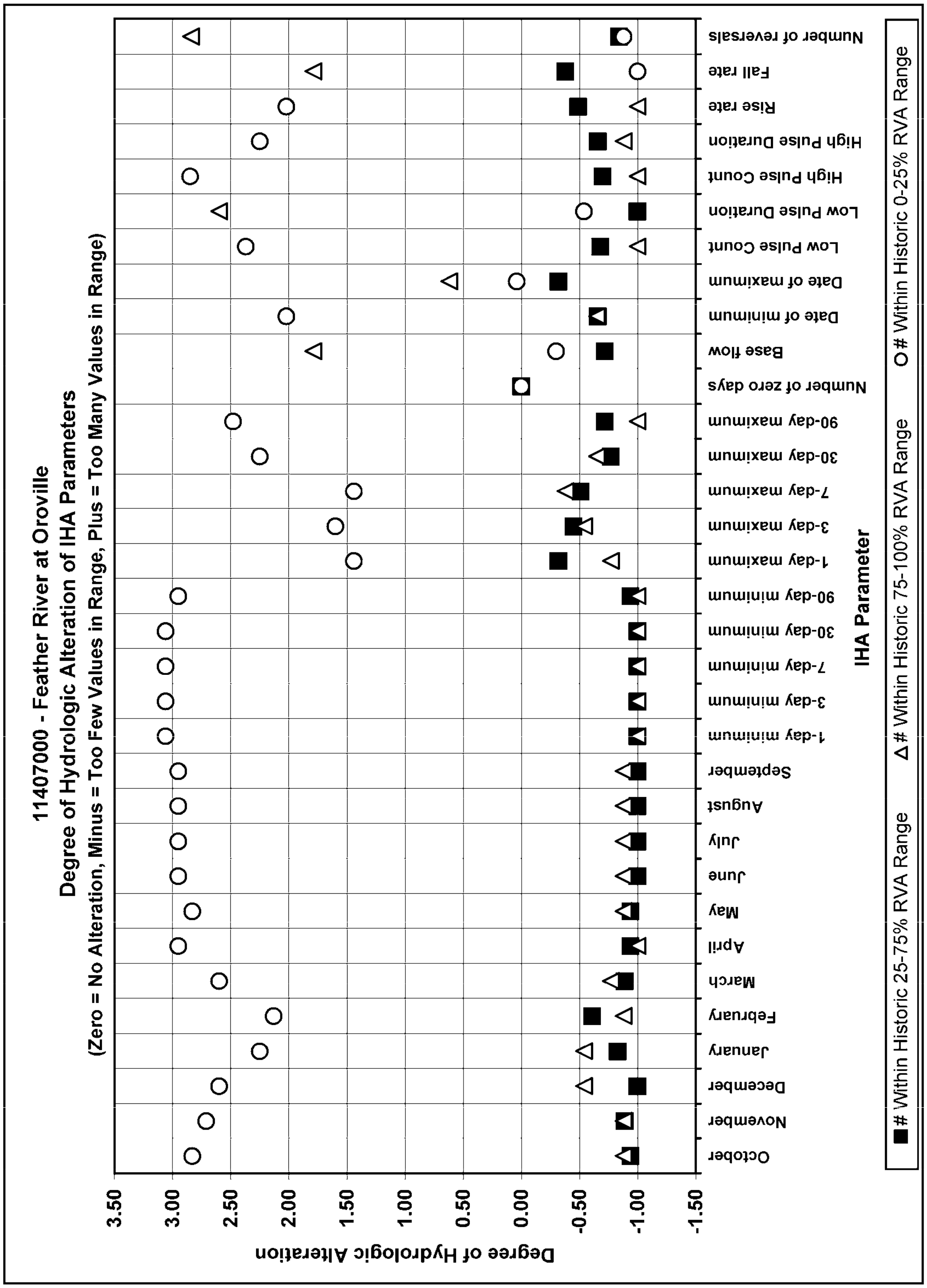

Figure 5.2-2 IHA Analysis of the Feather River Low Flow Reach.

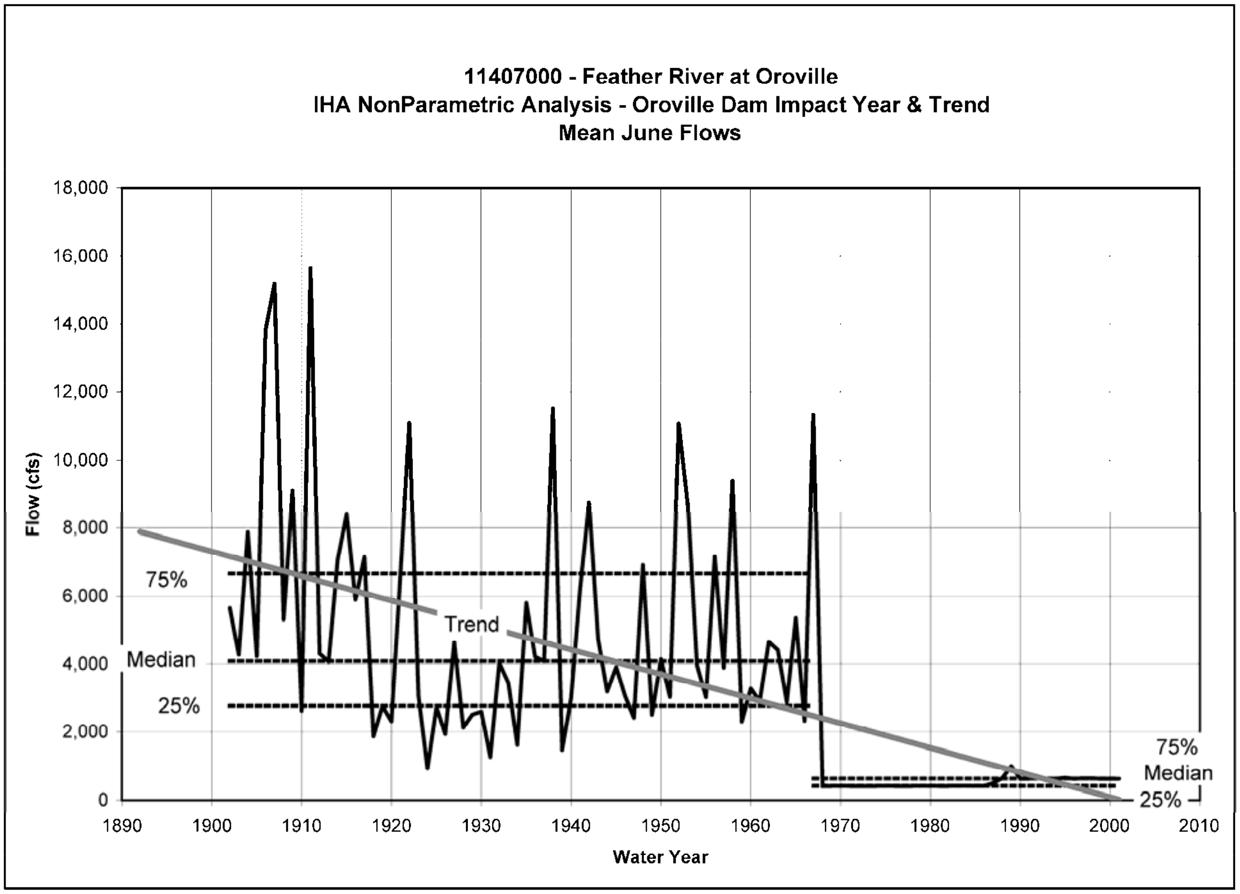

Figure 5.2-3 IHA analysis of Mean June flows in the Low Flow Reach.

5.2.3 Thermalito Afterbay to Yuba City Reach IHA Analysis

The second analysis was done for the reach between the Thermalito outfall and Yuba City. The pre-dam data used the Oroville gage, but the post dam data was calculated by adding Oroville gage and the Thermalito outfall stream flows. This excludes Honcut Creek, but its contribution is relatively minimal.

Figure 5.2-4 shows the alteration for the Feather River below the Thermalito outfall. The degree of alteration is less than that for the low flow reach, but some changes are significant. These include a decrease in both high and low flow pulses, a dramatic increase in summer flow, and moderate decreases in winter and spring flows. The figure shows the alteration graphically by degree of alteration. Figure 5.2-5 shows the yearly mean June flows for both the pre- and post dam periods. Also shown are the 25, median, and 75 percentiles.

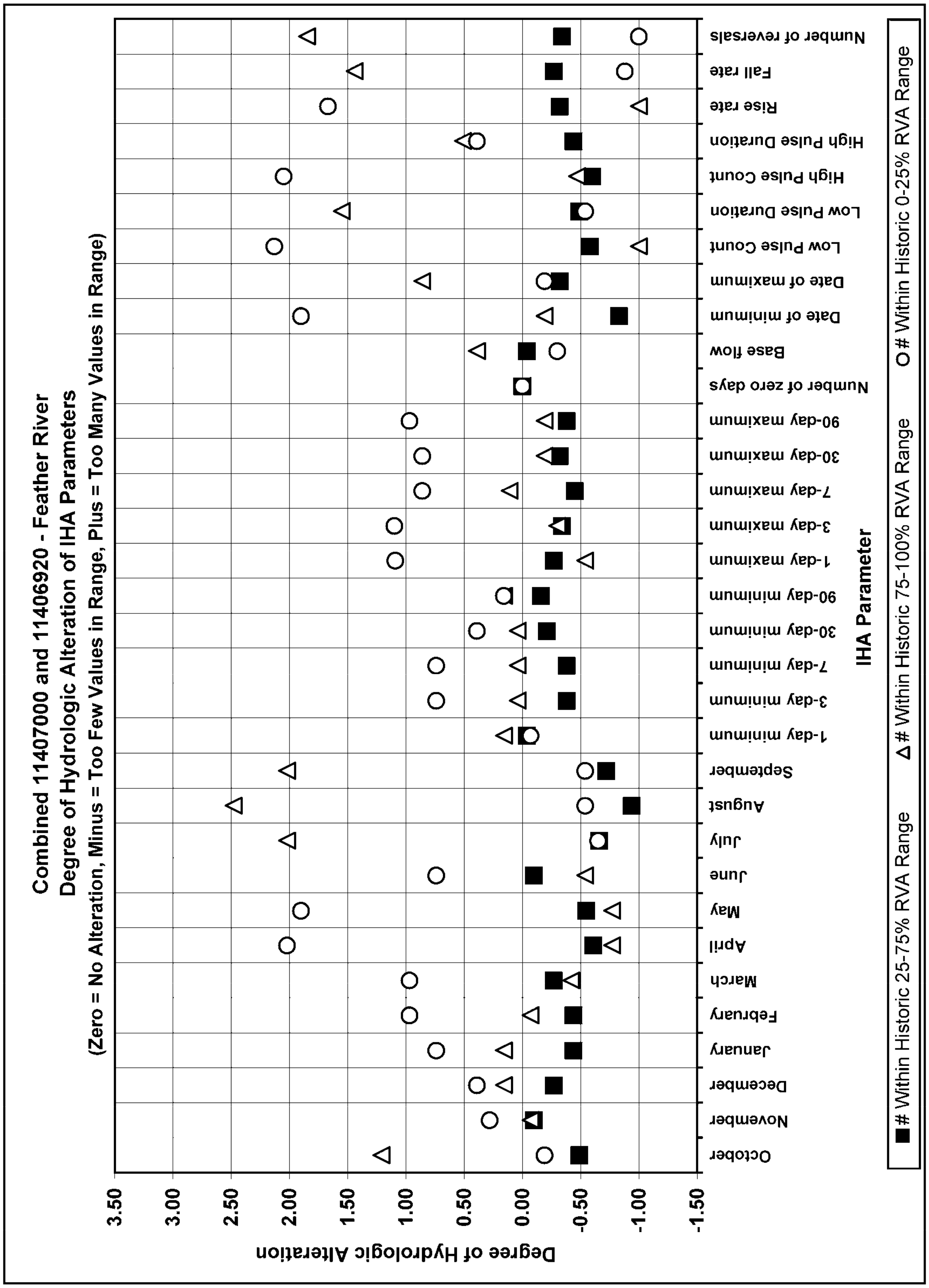

Figure 5.2-4 IHA Analysis of the Feather River High Flow Reach.

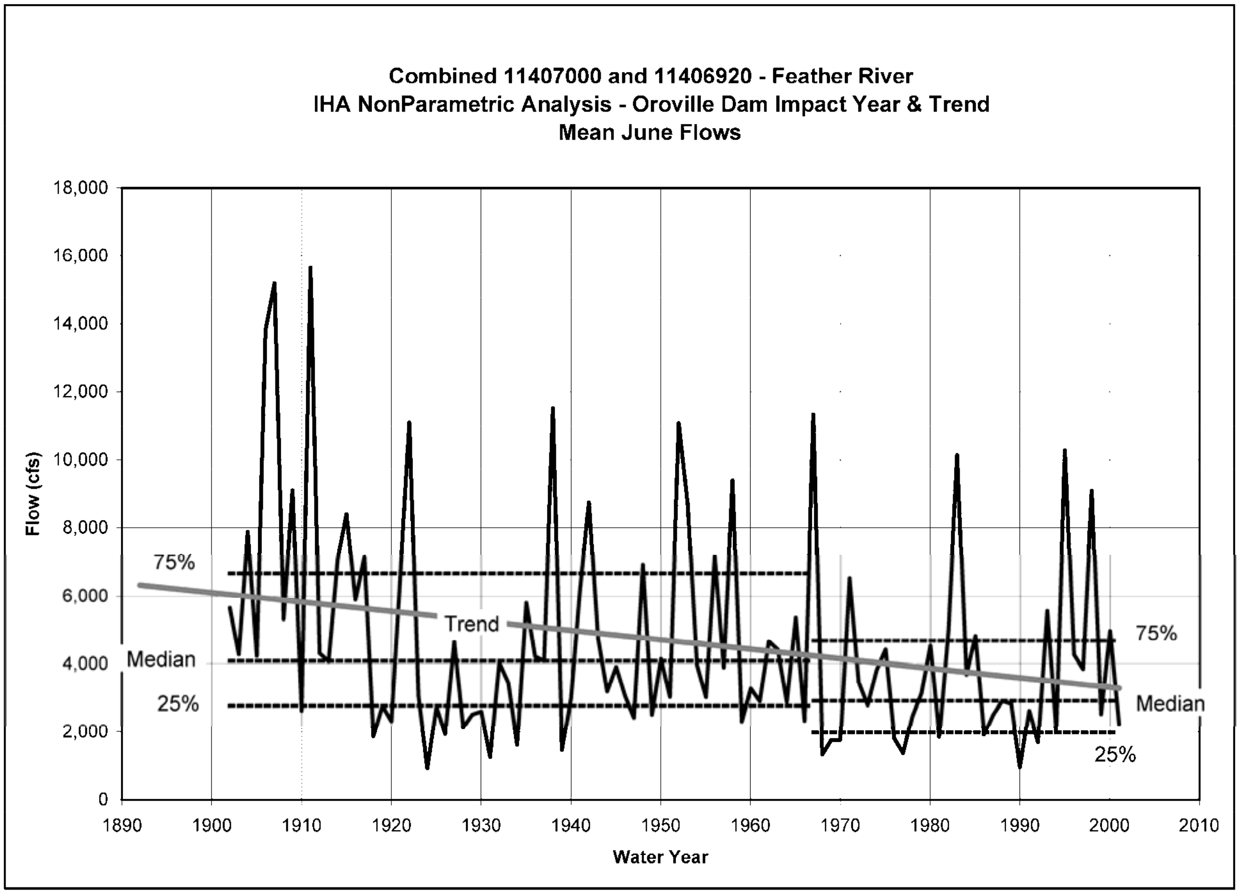

Figure 5.2-5 IHA Analysis of Mean June Flows for the High Flow Reach.

5.2.4 Yuba City to Verona Reach IHA Analysis

The third analysis was for the Feather River near Nicolaus gage. This analysis represents the part of the Feather between the confluence of the Yuba River and the mouth of the Feather near Verona. The reach includes streamflow from both the Yuba and Bear rivers.

Figure 5.2-6 shows the alteration for the Feather River near Nicolaus gage. Note that the degree of alteration caused by Oroville Dam is much less for the lower Feather River. This is caused by the influence of the Yuba and Bear rivers. The alteration in magnitude of mean monthly flows is low for the months October through June, and large only for July, August, and September. There is also a large shift in the timing and discharge of mean minimum flows. The maximum flows were shifted slightly below the median of pre-Oroville flows, thereby altered only to a low degree.

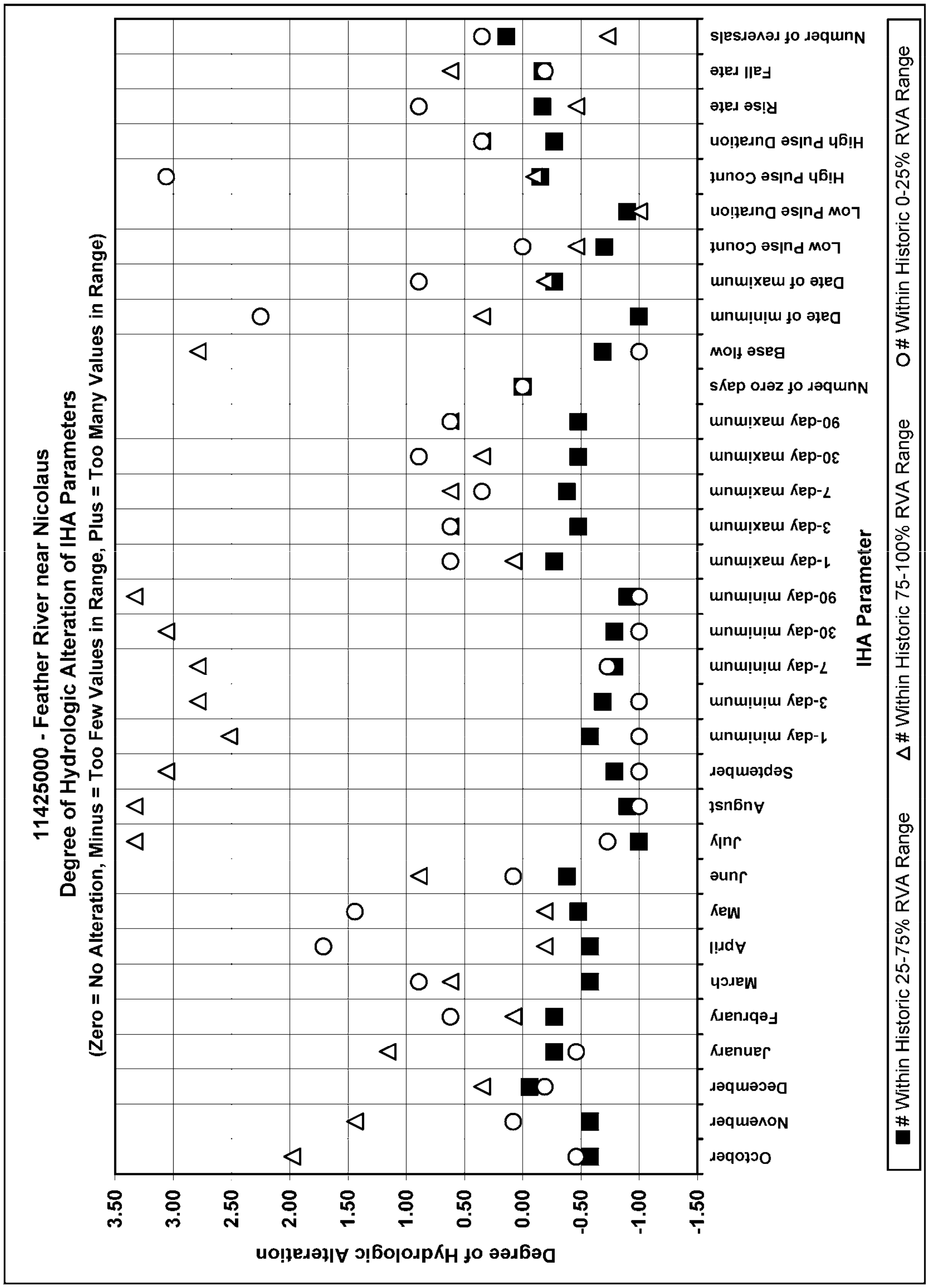

Figure 5.2-6 IHA Analysis of the Feather River between Yuba City and Verona.

Figure 5.2-7 is an example of IHA nonparametric analysis of mean June flows at the Nicolaus gage. Note that there are only relatively small changes in streamflow for the two hydrologic periods.

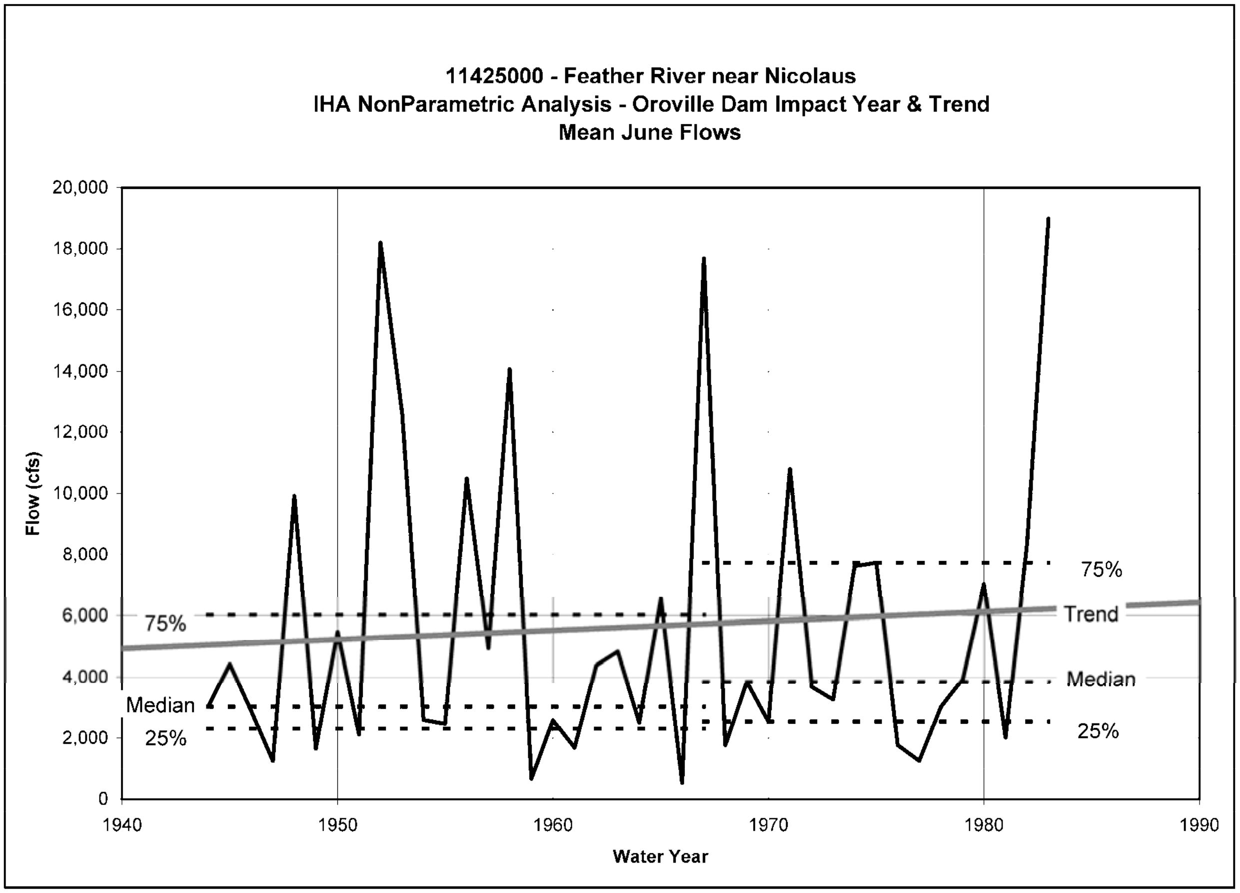

Figure 5.2-7 IHA Analysis of Mean June Flows for the Yuba City to Verona Reach.

To summarize the Nicolaus gage RVA analysis, the following variables showed a low degree of alteration: mean October, November, December, January, February, March, April, May, and June monthly flows; annual 1-day, 3-day, 7-day, 30-day, and 90-day maximum flows; date of maximum; high pulse count and mean duration; rise and fall rates; and number of reversals.

Moderate alteration was the base flow and the number of low pulses. Large changes included the following: mean July, August, and September monthly flows; annual 1-day, 3-day, 7-day, 30-day, and 90-day minimum flows; date of minimum flow; and mean duration of low pulses.

There are several reasons for the lesser degree of hydrologic alteration. First, most of the flow diverted into Thermalito Afterbay is released back into the river at the

Thermalito Afterbay outfall. Second, Honcut Creek, the Yuba River, and the Bear River enter the Feather above the Nicolaus gage. This additional streamflow results in the reduction of the degree of alteration caused by Oroville Dam. Third, dams on the Yuba and Bear Rivers were already in place prior to the construction of Oroville Dam, thereby significantly affecting streamflow during the pre-Oroville dam hydrologic period.

6.0 PROJECT EFFECTS ON GEOMORPHOLOGY

Fluvial geomorphology is the study of river-related form, function, and evolution. The geomorphology of a stream may be affected by a large number of inter-related factors. These include changes in the watershed, such as rainfall, runoff, sediment yield, vegetation, timber harvesting, road building, fires, agriculture, volcanic eruptions, grazing, and major storm events. Also included are changes in the river, such as dams, hydraulic mining, levees, gravel mining, water diversions, bank protection, dredging, and others. Many of these changes are clearly caused by human activities. Changes may work in concert, resulting in cumulative impacts greater than the individual contributions. Other changes may work counter to each other. For example, timber harvesting and grazing in the upper watershed will generally increase sediment yield but dams will generally decrease the yield.

The Feather River below the Thermalito Diversion Dam to Verona is mostly an alluvial stream. An alluvial stream flows across its own sedimentary deposits of clay, silt, sand, and gravel. The river's shape, form, gradient, bed material, etc. are constantly changing in response to changes in sediment and streamflow.

A normal, mature alluvial stream winds across its floodplain, eroding the outside of the bend and depositing sand and gravel on the inside. During floods, silt and sand are deposited across the floodplain. On the Feather River, a variety of human induced changes has affected this balance between erosion and deposition.

A meander belt is defined as the area in which a meandering river shifts its channel from time to time. It is delineated by lines drawn tangentially to the extreme limits of all fully developed meanders. The historic meander belt is defined as the area enclosed by all Holocene (last 10,000 years) meander deposits. The 100-year meander belt is also commonly defined because of the general availability of surveys, maps, and photos for that time period, allowing for accurate delineation of the boundaries.

The meander belt consists of Recent alluvium (Qa) and stream channel deposits (Qsc). The alluvium is older, but both consist of river deposits, including floodplain deposits, point bar deposits, channel fill, oxbow lake deposits, tributary delta deposits, and hydraulic mining debris. The deposits range in size from clay, silt, and sand to gravel, cobbles, and boulders. The coarse deposits predominate near Oroville and the fine deposits predominate from Gridley and downstream.

The geology and the historic meander belt are described and shown in the Task 1.2 Report. A more detailed mapping of the 100-year meander belt units are shown on the Aerial Photo Atlas for the Task 6 report and on the Oroville FERC Geographic Information System.

Older alluvial deposits not directly linked to the present Feather River form terraces on both sides of the active stream channel. These deposits are typically higher in elevation, more resistant to erosion, and define the boundaries of the active meander belt.

6.1 HUMAN INDUCED CHANGES IN GEOMORPHOLOGY

Human induced changes to the Feather River were discussed in detail in the Task 1.2 report. By far the largest impact was caused by hydraulic mining. Massive amounts of sediment were washed from Eocene gold-bearing gravel deposits and into the river. This included cobbles, gravel, sand, silt, and clay. The clay is orange to yellow and commonly referred to as "slickens".

As a result of hydraulic mining and other human induced changes, the Feather River today is very different from the Feather River that existed prior to the 1850s. The changes are purely anecdotal, since no survey data are available prior to the 1850s.

The following is a quote from Mendell (1875, in WET 1991) describing conditions prior to hydraulic mining:

"The….. physical condition of the Feather River is something wonderful, when we know that in 1849 it was the counterpart of the present Sacramento in all respects, namely, a succession of deep pools, separated from each other by shallow bars, the water being remarkably clear. At present day, all the pools along the Feather River have been filled up with washings from hydraulic mines, and changed into broad flats, covered with a sheet of water densely charged with sediment, and often barely 2 feet in depth, the only deep water being where the channel is contracted to 300 feet or less. An idea of the extent to which this filling has taken place can be appreciated when I state that the bottom of the river today is…. level with the tule - lands enclosed by the levees. These same pools in 1849 contained fully 30 feet of water where now there is scant 2 feet, and the bars have also been covered with sand so as no longer to be seen."

The present day Feather River is still profoundly affected by the mining debris. Both the cobble banks and the slickens have increased bank stability. Between Oroville and Gridley, cobbles and coarse gravel dredge tailings constitute most of the banks, slowing the bank erosion process. Between Honcut Creek and the mouth, the meandering process has slowed, and the river is wide, shallow, with low sinuosity and a sand bed. Most of the reach is mapped as glides or long pools, with low mesohabitat variability.

As a result of the hydraulic mining, the Feather River has changed character in the following ways:

- The river flows on a topographic high, as shown in Figure 6.1-1 (WET 1990), caused by deposition of hydraulic mining debris, with flood basins to the west and east generally lower than the stream thalweg.

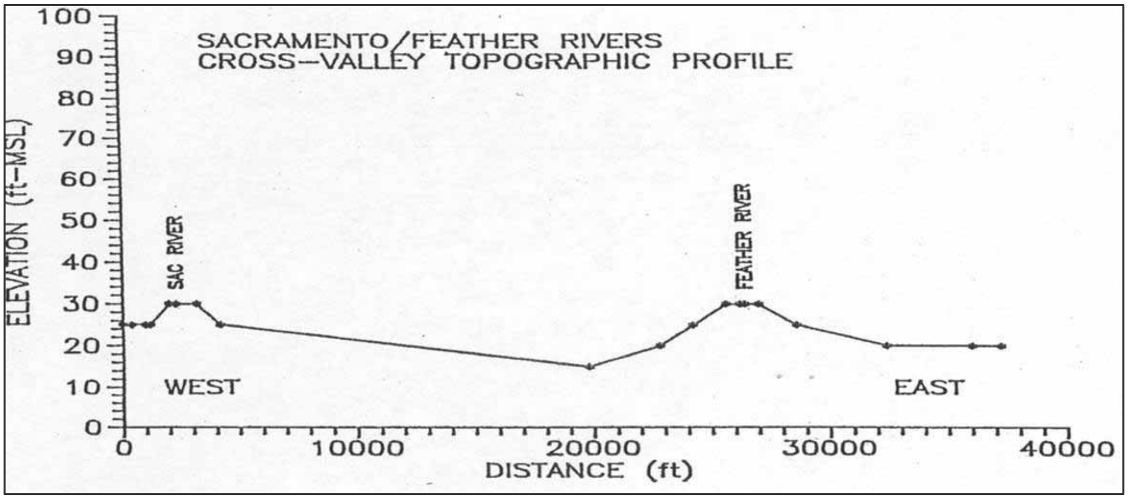

Figure 6.1-1 Cross - Valley Topographic Profile of Sacramento and Feather Rivers.

- Bank erosion is less. Stable clay (slickens) and cobble banks (dredge tailings) increase bank stability and reduce bank erosion. Less bank erosion means impacts on meander rates, riparian succession, and sediment in the stream.

- The river has become entrenched. Cross - section analyses by the USGS (1972) shows that the channel thalweg has been scoured down as much as 6 feet, and the cross - sectional area has increased as much as 400 percent between 1909 and 1970.

- Meander rates have been reduced. Meandering is the primary source of stream mesohabitat diversity. Meandering is primarily responsible for the creation of oxbow lakes, multiple channels, side channels, islands, point bars, large woody debris, riffle and pool habitat, and other features.

- Gravel recruitment for salmon spawning riffles is less. Bank erosion of silt - gravel composite banks is one of the main sources of gravel for salmon spawning riffles. Bank erosion has been reduced for the following reasons. First, banks in the upper reach have become less erosion prone because of the coarse dredge tailings. Second, the lower reach is more stable because it is incised in slickens. The original silt - gravel banks still remain buried under hydraulic mining debris.

The geomorphic changes that have occurred have many causes, as discussed above and in the Task 1.2 report. The purpose of this report is to determine what, or to what degree, additional changes are caused by the Oroville facilities. The procedure for determining the changes attributable to the project includes the following:

- Divide observational data into pre- and post dam periods.
- Determine pre- dam ongoing changes to determine trends not attributable to the project.
- Compare pre- and post project trends to determine elements of trends that are attributable to the project.
- Quantify the geomorphic effects of the project where possible.

6.2 CHANGES IN BANKFULL DISCHARGE

Water discharge and velocity affect sediment movement and deposition, and therefore also affect river morphology. It might seem that unusually heavy flows should erode away the channels, creating large channel cross sections to accommodate infrequent heavy flows, but this is not the case for meandering, alluvial streams. In fact, it is the more frequent intermediate flow that really control channel size and depth. Because of their frequency, they undo the work of the larger infrequent events. This intermediate flow is termed "bankfull discharge".

Bankfull discharge is therefore considered to be the geomorphic flow, that is, the flow most responsible for shaping the channel form and function. Bankfull discharge, in a natural un-dammed river is defined as the flow that occurs on an average about every two years. A bankfull discharge fills the channel but does not inundate the floodplain. Bankfull discharges meet the following two criteria for shaping channel cross sections:

- The flows are strong enough to erode banks and transport and deposit sediment.

- The flows occur often enough to overcome the effects of larger flows.

The installation of a dam on a river disrupts the frequency of an established bankfull discharge. The pre-dam bankfull discharge (2-year event) for the Feather River at Oroville gage was about 65,000 cfs. The post dam 2-year recurrence interval event for the Low Flow reach is about 2,000 cfs, a much smaller event that is not capable of transporting significant quantities of bedload or erode river banks. The 65,000 cfs flow now occurs at a lower frequency level of about every 10 years. The High Flow Reach now has a bankfull discharge of 26,000 cfs, also smaller than the pre-project event of 65,000 cfs.

Flows are reduced most of the time below dams. However, periodic releases from dams for flood control are sometimes larger flows than natural bankfull events. As a result, these flows erode the channels and banks. Generally few appropriate bankfull events occur to offset this. In addition, sediment is captured by the dam, resulting in minimal replacement of the sediment eroded during the bankfull event.

On the Feather River, an unusual condition exists where the bankfull discharge has decreased, but the channel capacity has increased.

6.3 CHANGES MEANDERING AND SINUOSITY

DWR compiled pre- and post Oroville Dam meander lines. Existing survey, topographic, and photographic data were collected. Aerial photos and maps were ortho-rectified by DWR Photogrammetry. Bank lines were digitized and individual erosion sites identified and analyzed by DWR Central District. The information was then entered into a GIS system. Pre- dam erosion and meandering were derived by comparing 1909 and 1965 data. Post dam was measured by comparing 1965 and 2001 aerial photographs.

Bank erosion sites were identified by shifts in bank line, and the average amount of bank recession was measured by using the area and dividing by the bank length. The maximum bank erosion and direction of movement were also measured.

Channel locations for the years available on the atlas and the GIS are published in the Task 6 Report. Changes in channel location, islands, multiple channel areas, levees, and riprap were also mapped and presented.

Ongoing impacts of the dam were determined by comparing pre- and post dam bank erosion and channel migration rates, island and multiple channel formation rates, gravel bars, riffles, channel width, gradient, and other geomorphic characteristics.

6.3.1 Channel Meandering and Erosion

Survey maps from 1911 and air photos from 1967 were rectified and the amount of bank movement measured in acres was an average of 18 acres per year. Subsequently, the 1967 photos were compared to the 2001 photos to determine about 13.5 acres per year of bank recession during the post dam period, or about a 28 percent overall decrease in bank erosion. Note that some of this reduction is caused by rock riprap bank protection and other factors. Installation dates are not known, but it is assumed that a substantial portion of the rip rap was installed after 1967. About 10 percent of the more erodible banks have been protected to date.

DWR compiled pre- and post Oroville Dam meander lines. Pre-dam erosion and meandering was derived by comparing 1909 and 1967 topographic mapping and aerial photographs. Post dam was measured by comparing 1967 and 2001 aerial photographs. Bank erosion sites were identified by shifts in bank line, and the average amount of bank recession was calculated by dividing the acreage of bank movement by the number of years between bank lines. The sites selected by river mile and the area of bank line migration are shown in Appendix A of the Task 6 report. The total acreage of change between 1909 and 1967 was 1,050 acres for a rate of 18.1 acres per year or an average of 2.26 sq. ft./ft./year. The total acreage of change between 1967 and 2001 was 460 acres for a rate of 13.5 acres per year or an average of 1.69 sq. ft./ft./year.

Overall the rate of channel migration for the Feather River is very low especially when compared to the Sacramento River between Chico and Colusa where the average rate of migration is 6.7 sq. ft./ft/year (DWR 1994) or Red Bluff to Chico with an average rate of 14.2 sq.ft./ft./year (DWR 1994). The Feather River has a relatively narrow meander belt and also is currently partially entrenched into the slickens deposits of hydraulic mining debris. The average rate of meander has decreased since the completion of Oroville Dam. The most likely reason for this reduction is the decrease in the frequency of channel forming flow events.

Some eroding banks have increased rates of post dam erosion. It is not clear why, but several possibilities exist. Bank erosion rates typically increase with a decrease in the radius of curvature and as these banks continue to erode, the radius decreases. A second possibility is that a more erodible soil type has been encountered. Third, ranch management may be increasing bank erosion. For example, irrigation resulting in saturated banks and seepage will generally promote bank failure.

From the preceding discussion, it is apparent that project facilities have reduced bank erosion by some amount. The 28 percent reduction cannot be attributed to the project alone, since about 10 percent of the eroding banks were protected by rock riprap at some point during the study period. These results should be tempered with the knowledge that the pre- and post dam periods were of unequal length, and that the frequency and magnitude of flood flows were different.

Bank protection or rip-rap occurs in many places on the Feather River. Bank protection consists of basalt quarry rock, cobbles, or concrete rubble. Minor bank protection occurs in the low flow section, at the Highway 70 bridge, just above Robinson Riffle, at the inlet and outlet weirs in the Oroville wildlife area, and at the Thermalito outfall. Between the Thermalito outfall and Honcut Creek rip-rap occurs extensively on both banks near Gridley and down stream, River Miles 51 to 47.5. Over 20,000 feet of rip-rap or 13 percent of the bank is rip-rapped in this 14.7 mile stretch

Between Honcut Creek and Sunset Pumps there is over 10,000 feet of rip-rap. Major areas are the left bank below Honcut Creek, the left bank above and the right bank below the Live Oak launch ramp, and the left bank above the Sunset diversion. Over 18 percent of the bank is rip-rapped in this 5.2 mile stretch.

Between Sunset Pumps and Yuba City 7,250 feet of the right bank but only 250 feet of the left bank is rip-rapped. The riprap occurs mainly on the outside of bends against the levee on the right bank and at bridges. A total of just over 6 percent of the bank is rip-rapped in this 11 mile stretch.

Riprap below Yuba City is common but not extensive. There are over 25,000 feet of rip-rap with most occurring on the left bank along the levee in the lower 7 miles. About 8 percent of the banks are rip-rapped in the 28 mile stretch from Yuba City to Verona.

Overall about 64,000 feet or10 percent of the banks of the Feather River are rip-rapped. WET (1990,1991) summarizes the extent of riprap for the Feather River from the Thermalito outfall to Verona. Location of riprap is shown on the Feather River Geology Mapping Atlas from Task 6 and in the Geographic Information System.

Bank erosion varies greatly depending on bank composition. Sand banks are the most erodible, followed by sandy gravel banks. Coarser gravel and cobble banks tend to be more erosion resistant, and erode at relatively slow rates. Banks consisting of clay and silt also erode at slow rates, primarily because of the cohesive nature of clay. The more clay found in the bank, the slower the bank erosion rate.

Slickens resulting from hydraulic mining contain abundant clay and subsequently have slow bank erosion rates. An analysis by Water Engineering and Technology (WET 1990) of two samples showed an average of 60 percent sand, 18 percent silt, and 22 percent clay. This is a high clay content for an alluvial bank and explains the low erodibility.

Banks composed of the Modesto and Riverbank terrace deposits also contain clay, are stable, but can erode when exposed to high velocity streamflow for long periods of time. In places, the Laguna Formation was observed to underlie the terrace deposits. The terrace deposits are considered to be the edge of the meander belt. The Modesto Formation is considered to be geologic control, that is, more resistant to erosion and providing longer term stability with low erosion rates. Where exposed, the Modesto forms light gray, tall, vertical banks. The Modesto banks average about five feet higher than the more recent alluvial banks. Bank undercutting and by block failure are the common sequence of events leading up to bank failure in Modesto deposits. The total length of Modesto banks is about 30,000 feet or about 5 percent of the total bank length.

Composite banks of recent floodplain deposits underlain by slickens are common in the lower river. These banks do not erode quickly because of a stable, clay-rich toe. The overlying sand and silt erode by fluvial entrainment or by dry ravel. Sand and gravel point bar deposits with overlying silt and clay floodplain deposits erode in a similar manner, with fluvial entrainment of the point bar deposits, followed by cantilever and block failure of the overlying deposits.

Banks composed of oxbow lake (clay plugs and abandoned channel fill) deposits also tend to be erosion resistant because of the higher clay content.

Bedrock units are considered non-erodible for this study. The Task 7 Report discusses the relative estimated erodibility of the geologic units. The erodibility factor used for the FLUVIAL 12 computer program is also shown in the report.

Bank erosion rates can change because of a number of factors. First, the bank material will change as the river erodes across its meander belt. Second, bend morphology changes with time. Chute cutoffs are the most common of these, resulting in an increase in the radius of curvature. The result is that dramatic shifts in bank erosion loci and rates can occur as a result of these events that are unrelated to project effects. The number and intensity of flood events also affect bank erosion rates. These factors should be kept in mind when evaluating pre- and post dam erosion rates.

Bank failure processes are similar to that of the lower Sacramento River in that failure modes are highly correlated with bank materials.

The upper reach banks are composed of geologic control, cobble mining debris, normal floodplain deposits, or a combination of slickens on the bottom and floodplain deposits on top. The eroding banks of the lower Feather are composed of either Modesto Formation, or a composite bank of slickens and floodplain deposits. Banks consisting of alluvial bar deposits also occur, but these generally do not erode since they are generally located on the inside of bends.

Banks with a uniform composition normally have rotational failures or block failures. These include abandoned channel fills and floodplain deposits consisting mostly of silt and sand.

Bank erosion occurs on bends and straight reaches. Rates tend to be higher in bends than straight reaches. Bend morphology is such that velocities are higher along the outside, eroding and undercutting the bank. The smaller the radius of curvature, the sharper the bend, and the more erosion occurs. The low sinuosity of the Feather, however, means that there are far more straight banks than curved.

Bank erosion is affected by bank moisture. Dry banks erode at a slower rate, all other factors being equal. Wet banks lose soil cohesion, and the water adds weight. Receding flows after bank full discharge tend to be the most erodible because banks are saturated, positive seepage pressures causing piping and liquefaction, and lack of support and buoyancy from receding flows.

At some point in the future, the river will degrade through the mining deposits. Banks will then again be composed of sand and silt in the lower layers. This may increase bank erosion rates dramatically, since these lower banks would be highly erodible. Bank undercutting would result in upper bank failure as well.

6.3.2 Changes in Sinuosity

Sinuosity is measured from topographic maps. Sinuosity is defined as the ratio of river length to down-valley length, and is an expression of the size and number of curves.

Overall, the study reach has an average sinuosity ratio of 1.21 from the Fish Barrier Dam to Verona. The reach between the Fish Barrier Dam and Yuba City has an average sinuosity of 1.29, and Yuba City to Verona Reach has an average sinuosity of 1.1.

Comparison of sinuosities from maps and aerial photographs shows that there has been a drop in sinuosity in the last century. Most of this reduction occurred below Yuba City. Evidence from maps and aerial photographs suggest that the drop in sinuosity from about 1.2 to 1.1 in this area is partially the result of dredging operations in the lower part of the river. A number of the point bars were cut through in the early 1900s, probably for the purpose of shortening the river for navigation.

There are local places where the sinuosity has increased, such as the area directly above Honcut Creek.

The combination of historical observations and present day channel sinuosity suggest that the Feather River was more sinuous prior to hydraulic mining than today (WET 1990). The present-day sinuosity is not substantially different from those of the 1920s. Because of the entrenchment of the Feather into hydraulic mining debris and flood control from Lake Oroville, it is expected that the sinuosity will not change substantially in the next fifty years or so.

The change in sinuosity attributable to Project facilities was investigated in Task 6 by comparing pre- and post Project maps and photographs dating from 1907 to 2001. The total amount of change was small. Most of the changes in sinuosity occurred in the early 1900s. There have been no significant changes in sinuosity since the Oroville Project was completed in 1967. This indicates that any change in sinuosity attributable to the Project must also be small.

6.4 CHANGES IN CHANNEL FORM

Dams may cause narrowing or widening of river channels below the dam structure. Dams typically reduce the magnitude of peak discharge. With fewer high water events flowing downstream, rivers adjust in order to reduce energy lost to friction.

The effects of a dam on downstream channel form depend on sediment availability. When sediment is available from tributaries, then sediment deposits in the channel in response to the diminished streamflow. This means channels will tend towards a narrower and deeper shape. Without annual flooding, small trees and shrubs on the banks are not washed away. Once thick vegetation is established, banks and sediments are stabilized, forcing the river to follow only one course. Channel narrowing has been greatest below reservoirs with the capacity to hold the river's largest floods. Channel narrowing is associated with environmental problems such as lowered groundwater tables and destruction of riparian habitats.

When sediment is not available, bank and bed erosion occurs in the channel below the dam. This process is occurring on the Feather River. Infrequent high flows scour the channel but no sediment moves in from above to replace the washed out sediment. The channel becomes wider and deeper with time.

The Feather is still adjusting to changes caused by hydraulic mining and dam construction. Several studies provide information on these changes. The USGS (1972) documented channel changes between 1909-1911 and 1970 on a number of cross-sections. Masters theses by James (1989) and Wildman (1981) provide information about general post hydraulic mining degradation, particularly on the Yuba and Bear River tributaries.

6.4.1 Channel Cross-section, Depth, and Width

DWR, as part of this study, compared three sets of cross-sections. The first set consisted of cross-sections surveyed between 1907 and 1911 by the California Debris Commission and the Army Corps of Engineers between Oroville and Verona. Soundings were done at intervals. DWR scanned and entered the maps into a coordinate system. Cross-sections were developed in areas with river depth information. These were compared to cross-sections developed from 2-foot contour maps surveyed by Ayers and Associates for the Corps. The topography was developed from 1997 aerial photographs and river soundings. This span includes both the pre- and post dam periods.

The second set compared 1952 cross-sections developed from U.S. Geological Survey topographic maps with the 1997 data. The contour interval was 5 feet, and channel location but no channel detail was available except for the channel width.

The third set compared the 1970 USGS cross-sections with 1997 cross-sections derived from the same two-foot contour maps developed by Ayers and Associates. The time interval between cross-sections approximates the post project period.

In addition, DWR re-surveyed in 2002-03 cross-sections surveyed in 1994. The 1994 cross-sections were prepared as part of IFIM modeling effort, and were not surveyed to a high degree of precision. This cross-section comparison may be useful in determining the effect of the January 1997 flood, the biggest post dam flow on record, but will not be discussed here.

Figure 6.3-1 shows pre-project changes in selected channel cross-sections between 1909-11 and 1970 (USGS 1978). During this time, the cross-sectional areas increased at most cross-sections to almost 400 percent at some. This increase in channel area is mostly a result of the post hydraulic mining era, when hydraulic mining debris was washing out of the system. The post mining degradation trend makes it more difficult to determine the additional effect of project facilities.

Some of the cross-sections surveyed show a large increase in channel area. A cross-section at RM 37.4 shows an 80 percent increase in channel area. The average depth increased by almost five feet. A cross-section at RM 41.9 shows a 250 percent increase in area with little change in depth. A cross-section RM 60.4 shows a 15 percent increase in area and about four feet of thalweg lowering. This has also dramatically increased channel capacity and the ability of convey flood water without flooding. The increase in depth and width is characteristic of the entire lower Feather River.

The 1909-11 cross-sections were compared with 1997 cross-sections developed from 2-foot contour maps surveyed by Ayers and Associates. About 45 channel cross-sections were plotted between River Mile 67 and RM 28. During this time period, 30 cross-sections widened, 8 narrowed, and 7 showed minimal change. Degradation occurred on 40 cross-sections, 3 aggraded, and 1 showed no change. The average amount of thalweg lowering was between 6 and 8 feet, or 0.08 feet per year. These are discussed in more detail in the Task 3 Report.

The 1952 to 1997 comparison included 34 cross-sections, of which 15 widened, 14 stayed about the same, and 6 narrowed.

The third period includes 58 cross-sections surveyed by the USGS in 1970 compared to the 1997 data. This roughly approximates the post Oroville project conditions. The channel width narrowed on 10 cross-sections (17 percent), widened on 22 (38 percent), and showed no change on 26 (45 percent). In this period, 31 cross-sections degraded, 12 sections showed no change, and 8 aggraded. The river continues to degrade in the post project period.

The average degradation is -0.66 feet averaged by cross-section, or -1.0 averaged by river mile. This results in a rate of about 0.04 feet per year, or about half of the 1907-11 to 1997 rate.

Comparing the 1907-11 and 1997 data with the 1970 and 1997 data suggests that the degradation process has slowed considerably during the post project period. For example, the 1907-11 to 1998 period had 33 percent of the cross-sections narrowing or showing no change compared to 63 percent for the1972-1998 period.

The dramatic increase in cross-sectional area since 1907-11 can be attributed to the following:

- The influx of large amounts of mining debris, followed by cessation of mining, and subsequent channel widening and incision through the process of bank and bed erosion;
- The capture of sediment behind Oroville dam since 1967. Without sediment transport, there is no replacement of sediment eroded from the banks and the bed. The reduced flood flows attributed to the Oroville Dam's flood control function would tend to reduce this effect.
- The mining of gravel for Oroville facilities construction and commercial purposes.

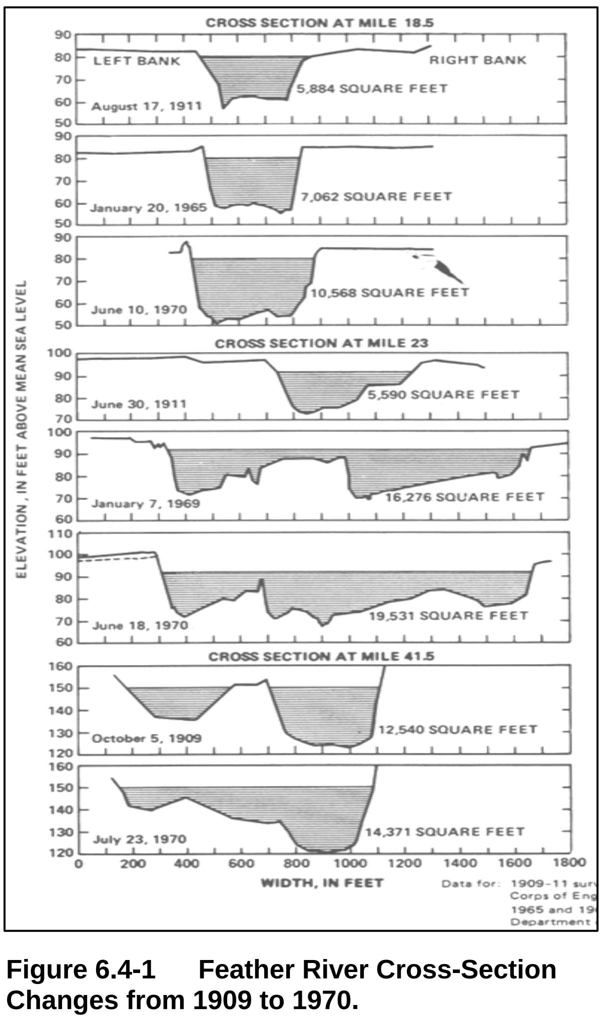

Figure 6.4-1 Feather River Cross-Section Changes from 1909 to 1970.

The purpose of this discussion is not to absolve Oroville facilities of any responsibility for the degradation process but to put it in historical perspective. The post mining degradation is naturally slowing down with time as the channel readjusts to the drop in sediment supply. In addition, Oroville Dam captures any additional sediment that would normally replenish sediment washed out, thereby increasing the rate of degradation. At the same time, the Dam controls floodflows, reducing the natural incidence of channel-forming flows. This tends to decrease the degradation rate.

6.4.2 Channel Profile

Gradient is defined as the ratio of the change in elevation of the water surface over a selected stream length. It can be expressed as feet per mile or as feet per feet, preferable because it is a dimensionless quantity. The gradient is not constant. River reaches are divided into riffle/run/glide/pool segments with a large variation in gradient.

Water Engineering and Technology (WET 1990,1991) plotted the thalweg profiles from 1909 and 1964 surveys from Verona to the Fish Barrier Dam. The overall gradient of the reach is 0.3 feet per 1,000 feet. The gradient from the Fish Barrier Dam to Yuba City is 0.5, and the Yuba City to Verona reach is 0.2 feet per 1,000 feet.

Their plot shows the amount of thalweg degradation between 1909 and 1964 to be about 10 feet. Degradation increases dramatically downstream. Maximum thalweg degradation was about 25 feet, occurring near RM 28. There are two reasons for the increase in degradation downstream. The first is that less hydraulic mining material deposited in the upper reach. The second is that the material was coarser and less erodible in the upstream reach.

The ongoing post hydraulic mining degradation of the channel thalweg complicates the determination of the Oroville Facilities effects. The dam affects the degradation rate in two significant ways. First, reduced flood flows and the reduction in bankfull discharge will decrease the degradation rate. Second, the trapping of sediment in the reservoir and the lack of sediment recruitment to the lower Feather will increase the degradation rate. Rock Creek Reservoir on the North Fork and Ponderosa on the South Fork and many other reservoirs in the watershed, capture sediment prior to reaching Lake Oroville and the loss of this sediment to the river system are not Oroville Facilities effects.

As part of Task 7, the FLUVIAL-12 modeling of channel bed profiles were done to predict changes over the next 50 years between RM 67 and RM 44. Both simulated peak water-surface and channel bed changes are shown in Figure 6.4-2. The channel-bed profile is the invert (or thalweg) elevation. Changes in channel-bed profile in this figure depict channel-bed aggradation and degradation (or fill and scour). Both aggradation and degradation are shown in the figure except more sections are predicted to undergo degradation than aggradation.

The channel degradation is consistent with the continued erosion. Future changes will be limited by bed armoring, which in turn, will reduce bed erosion and sediment yield. Future changes, as predicted by the model, will be small compared to the changes that have occurred to date.

The overall channel gradient for this reach will not change significantly. However, the model predicts that the channel thalweg will smoothen with time. This is a natural stream characteristic, resulting from increased erosion in the high gradient reaches and deposition in the low gradient reaches.

Between River Mile 44 and RM 0 at Verona, a large amount (over 20 feet in places) of degradation already occurred prior to the Project. Post hydraulic mining degradation still continues.

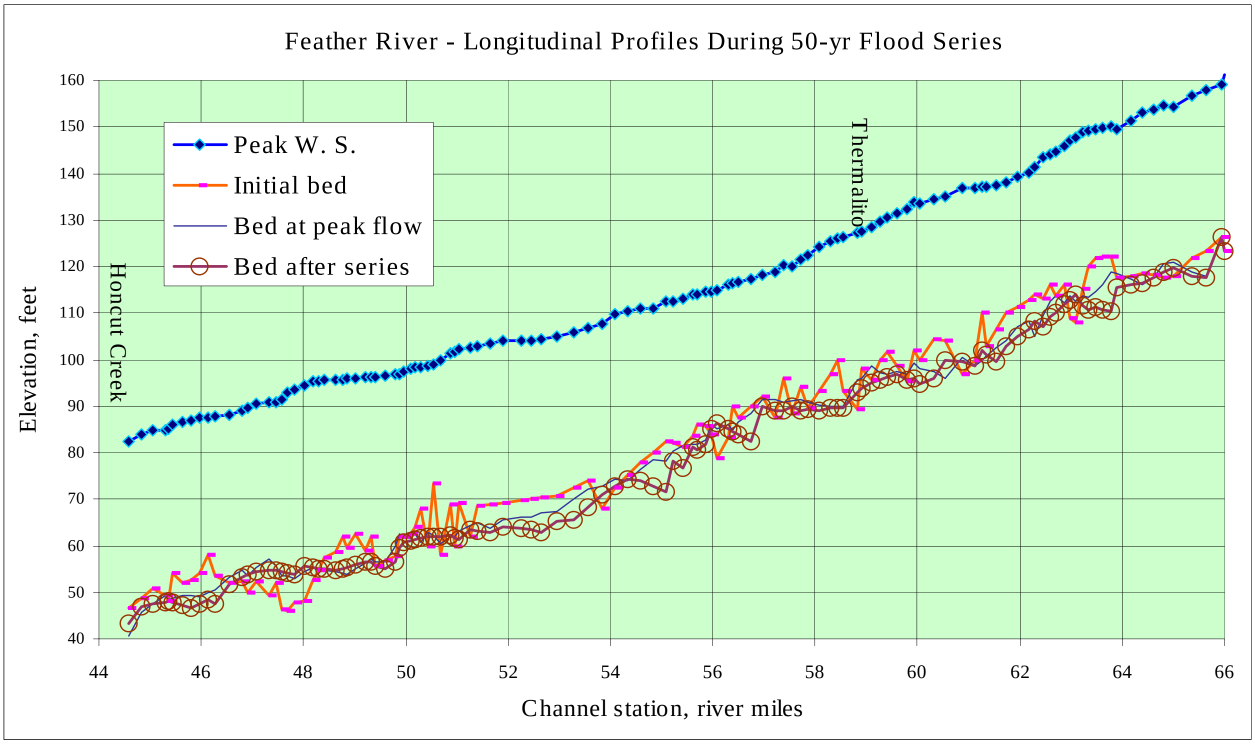

Figure 6.4-2 Modeled water-surface profile and channel-bed profile changes for the next 50 years.

Project facilities contribute to this continued degradation. The report for Study Plan G1 estimates the amount of sediment from upstream reaches deposited in the reservoir to be about 16,900 acre-feet, or 27 million cubic yards, from 1967 to 2003. This is the deficit amount of sediment to the lower river that can be attributed to Project operations. This is equivalent to covering the 67 miles of lower river channel with 6 to 9 feet of sediment.

6.4.3 Channel Roughness

Channel roughness is a function of the amount of riparian vegetation, type of bed material, channel shape and sinuosity. The roughness will change with changes in these factors. The roughness factor was increasing prior to the Oroville facilities as a result of the degradation process. During degradation, the finer material is washed away, leaving an armored bed with coarse lag deposits. The result is an increase in the channel roughness.

Additional degradation is likely associated with the Oroville facilities, resulting in an incremental increase in the roughness. The graph in Figure 6.4-3 shows the combined effect of long-term post mining degradation and FLUVIAL-12 modeled operation of the Oroville Facilities for the next 50 years. Coarsening occurs over most of the modeled reach. Since coarsening is related to an increase in roughness according to standard hydraulic equations, the roughness will also increase as a result of the Oroville Facilities operations.

The bed material size increase is similar to actual sampling conducted by DWR between 1980 and 2003, reported in the Task 2 report. There is limited information as to the coarsening of bed material in riffles and the effects on salmon spawning. The coarsening affects the ability of the salmon to excavate the bed during redd construction. The eggs may also wash out if the intragravel interstices are too large.

The increase in roughness and bed material size is mostly an impact related to the Damming of the River because of the sediment trapped in the reservoirs and the lack of sediment deposition downstream.

6.4.4 Stream Channel Classification

There is a lack of channel classification information prior to the construction of the Oroville facilities. This prevents a direct comparison of pre- and post dam classification. The predominant substrate, as shown in Table 6.4-1, does affect the subclass of the Level 1 stream type.

The coarsening and armoring attributed to operation of the Oroville facilities is expected to change the stream type to some degree. A C4 or C5 may, over time, become a C3 as the predominant substrate changes from sand and gravel to cobble. Similar changes can be expected for the other stream types.

The stream channel classification and the Rosgen geomorphic stream type (Rosgen and Silvey 1996) have been affected more by levees. Levees restrict the floodplain and change the ratio of channel width to floodplain width, a major factor in the stream classification system.

Changes in channel geometry also occur as bank erosion, bed erosion, and sediment transport move sediment out of the system. These changes affect the biological function of the stream system. Changes in depth, width, gradient, location of the thalweg, erosion, meandering, sinuosity, and other geomorphic factors affect the mesohabitat. These changes, in turn, affect the amount of riffle, run, or pool habitat, type of riparian habitat, and eroding bank habitat.

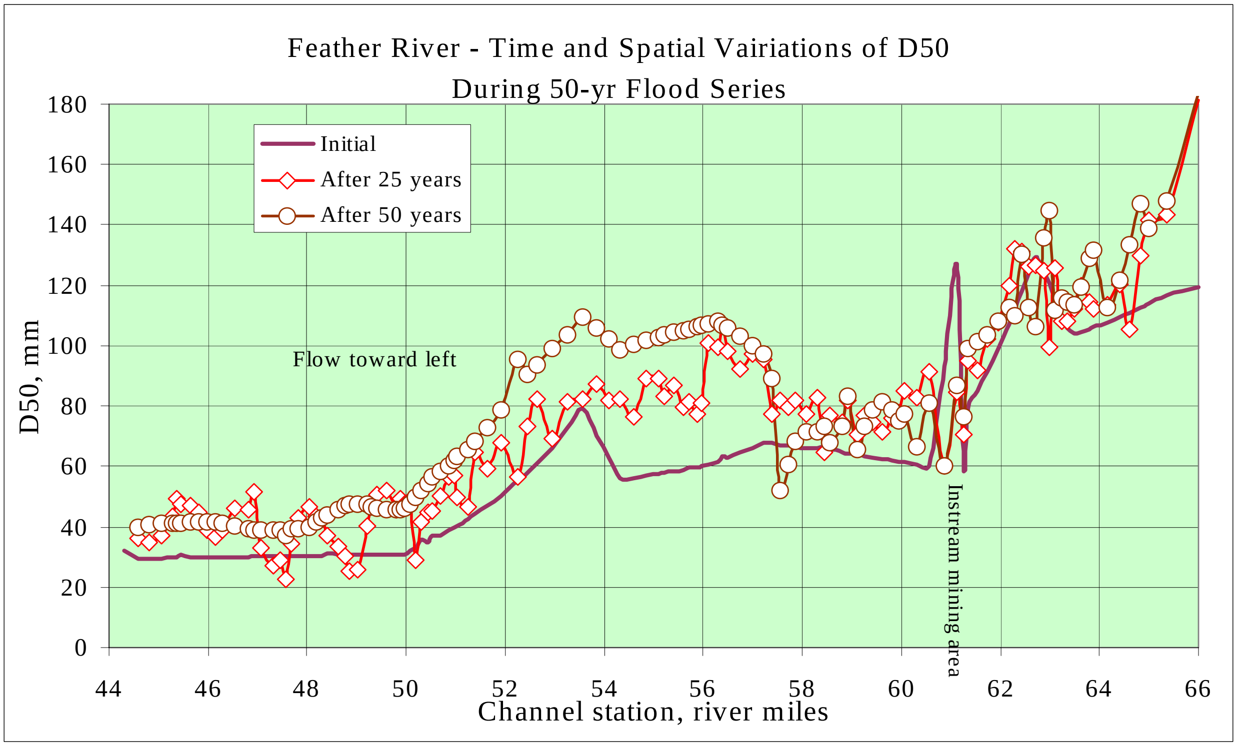

Figure 6.4-4 Change in Median Diameter of Sediment during a 50-Year FLUVIAL-12 Model Run.

Table 6.4-1 Rosgen Level 1 Stream Typing

COE River mile	DWR River mile	Slope	Predominant Substrate	Stream Type
66.3 - 65.3	67 - 66	0.1052%	Cobble and gravel	C4
65.3 - 64.4	66 - 65	0.0948%	Cobble and gravel	C4c -
64.4 - 64	65 - 64.6	0.0947%	Cobble	C3c -
64 - 61	64.6 - 61.5	0.1705%	Cobble	F3
61 - 60	61.5 - 60.25	0.0568%	Boulder	F2
60 - 59	60.25 - 59.35	0.0758%	Cobble and gravel	F4
59 - 54	59.35 - 54.5	0.0379%	Cobble	F3
54 - 53	54.5 - 53.45	0.0947%	Cobble and gravel	F4
53 - 52	53.45 - 52.4	0.0379%	Cobble	F3
52 - 49	52.4 - 49.05	0.0379%	Cobble and gravel	F4
49 - 48	49.05 - 47.8	0.0947%	Cobble	F3

48 - 47	47.8 - 46.7	0.0568%	50% Gravel/ 50% Sand	F4/5
47 - 46	46.7 - 45.8	0.0569%	Cobble	F3
46 - 45	45.8 - 44.7	0.0569%	Sand	F5
45 - 37	44.7 - 36.75	0.1137%	Gravel	F4
37 - 26	36.75 - 27.5	0.0000%	Sand	F5
25	26.5	0.0311	Bedrock Ledge	F1
	24 - 15	.02	Sand	F5
	14 - 0	.02	Sand	C4

7.0 PROJECT EFFECTS ON SEDIMENT

Changes in sedimentation cause significant geomorphic modifications both directly above and downstream of dams. Rates of deposition, transport of particles, and erosion are all dependent on stream flow velocity, the amount of suspended sediment and bedload, and particle size distribution.

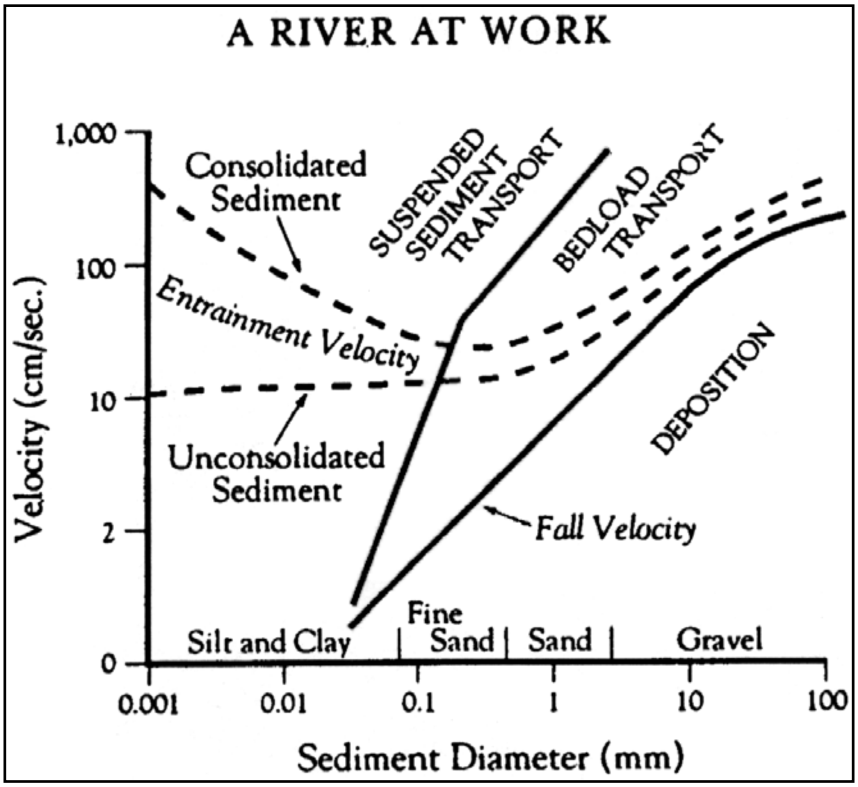

Figure 7.0-1. Modified Hjulstrom Diagram.

This graph, a modified Hjulstrom diagram (Mount 1995), shows that at low water velocities, smaller sediments are transported and larger sediments can settle to the bottom. At high velocities, erosion will occur. In addition, there are other factors that are not illustrated in this graph that affect the threshold velocities for the entrainment and transport of sediment. For example, very fine clay particles have electrostatically charged surfaces. They stick together and become cohesive in a process known as flocculation. Clay particles that flocculate are more difficult to transport than larger sand particles.

As discussed in the Task 1.2 Report, between 1855 and the early 20th century, a large increase in sediment resulting from hydraulic mining, resulted in a permanent change in river geomorphology. A thick deposit of fine clay-rich slickens was deposited in the channel and on the floodplain. As much as 20 feet of deposition was reported in Marysville. Much of the deposition occurred in the channel and adjacent overflow area. The result of this enormous increase in sediment is that the river is perched on these deposits above the surrounding floodplain, aggravating flooding during high flow events.

This was followed by cessation of mining (1895) and the gradual reduction of sediment as the hydraulic mining debris was washed downstream, resulting in a degradational regime. The construction of Oroville Dam in 1967 contributed to the trapping of almost all of the sediment derived from the upper Feather watershed. Dams on the Yuba and Bear rivers have had similar effects. This has resulted in the lower river becoming more degradational. Consequently, the river has eroded vertically through the hydraulic mining debris, leaving the slickens exposed in channel banks.

7.1 SEDIMENT DELIVERY

Sediment is the material that settles to the bottom of rivers and lakes. Sedimentation patterns depend on the flow rates of water and the size of particles. The installation of a dam disrupts the longitudinal flow of a stream or river. Upstream, sediment is deposited in the quiet waters of the reservoir. Large dams often have trap efficiencies of 90-100 percent meaning they catch between 90-100 percent of all the sediment from upstream. Heavy grazing and logging practices heighten sedimentation rates, and reservoirs downstream from such activities lose capacity.

It is difficult to predict the life expectancy of a reservoir because as land uses change, sedimentation rates change. Sedimentation above the dams is also likely to cause aggradation, or the filling in of the channels leading into the reservoirs. Most rivers have multiple dams along them, reducing the amount of sediment delivered downstream. This slows upstream profile changes and slows the delivery of sediment to reservoirs downstream, further complicating the calculation of lifetimes for reservoir. The report *SP-G1: Effects of Project Operations on Geomorphic Processes Upstream of Oroville Dam* (DWR 2004) details the movement of sediment into Lake Oroville.

The coarser, heavier particles will settle in the upper reaches of a reservoir, while the finer silts and clays will slowly settle in deeper areas. In some reservoirs, very fine particles can remain suspended and be released downstream, but the heavy gravel, sand, and rocks will settle quickly. Coarse materials entering reservoirs from the upper reaches of a river are quickly deposited in the still waters.

The water that is released from a dam is clear water or "hungry water". This clear water then erodes away the finer material and leaves the coarser grains. Since there is no replenishment of the gravel and sand below the dam, the bed material becomes coarser and coarser with time.

Sediment delivery is the amount of sediment moving past a specified point over a period of time. Delivery may be expressed as an average annual yield, or as a total amount over the planning period. Graphs of sediment yield versus river location shows the downstream movement of sediment.

The FLUVIAL-12 modeling study described in the Task 7 Report predicts ongoing changes in sediment delivery. The model was based on a 50-year flood series. The available flow records cover the time period from 1967 to 2002, which is 35 years in total duration. In order to simulate the flow of 50 years, part of the flow records was used twice. The 50-yr flood series selected for the modeling study has the starting date of October 1, 1997, consistent with the time of the Army Corps cross-sectional data measurement. The series used the flow record from 1997 to 2002, 1967 to 2002, and then 1967 to 1977 for a total of 50 years. A major peak flow is near the mid- point of the series on February 19, 1986, with a peak discharge of 150,000 cfs for the High Flow Reach and 134,000 for the Low Flow Reach. Sediment delivery predicted by FLUVIAL-12 for the next 50 years is shown in Figure 7.1-1.

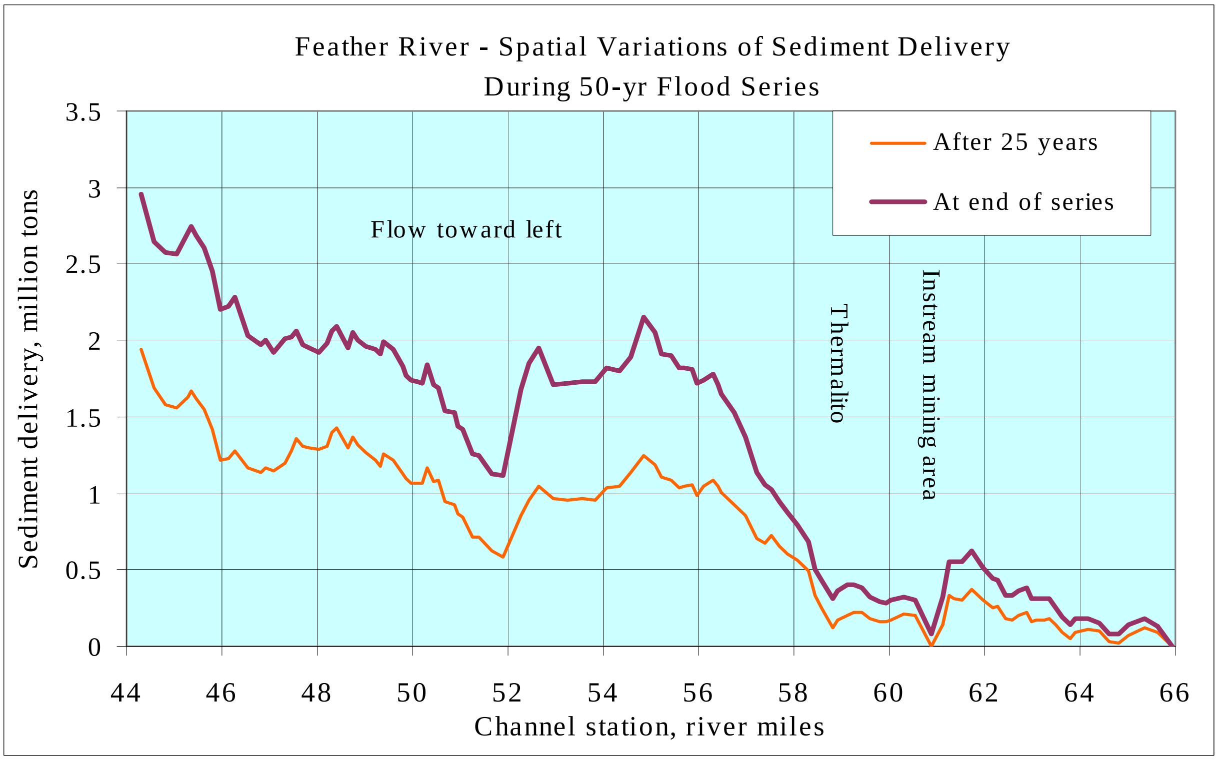

Figure 7.1-1 Time and spatial variation in sediment delivery during the 50-year flood series for armored bed.

The figure shows the amount of sediment moving past each river mile. The Feather River between the Fish Diversion Dam and Honcut Creek is not uniformly eroding, but also has areas where deposition is occurring. Some of these areas have been identified as past gravel mining areas. The location of sediment traps is important in designing Resource Actions such as gravel augmentation projects.

The pattern of spatial variations has a generally increasing trend toward downstream, with local exceptions. The increasing trend indicates net sediment removal from the channel reach. For the 50-yr time period, the net sediment removal is the increase in delivery from the upstream end to the downstream end of the study reach and this amount is about 2.9 million tons.

FLUVIAL-12 was also used to model the effect of the Oroville facilities on a natural, un-armored bed. This closely approximates conditions directly after dam closure and is a better estimate of the dam's effect. The net sediment removal of 2.9 million tons for an armored bed is much less that the net removal of 5.5 million tons for the natural channel bed.

The comparison of an armored and un-armored bed shows that sediment delivery largely slows down as the channel bed armors. This is further substantiated by comparing the 25 and 50 year sediment deliveries. The net sediment removal in the first 25 year time period is about 1.9 million tons and only 1 million tons in the second 25 years. From these numbers, it may be stated that sediment removal from the channel reach has a higher initial rate and the rate of removal slows down with time.

The pattern of sediment delivery shows a sharp rise in delivery in the Feather River just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary.

7.2 SEDIMENT YIELD

The USGS (1978) estimated the pre-dam daily mean discharge as 5,790 cfs and the total suspended sediment yield as 72,720,000 tons (1902-1962), or 3,262 tons per day. The estimated daily mean suspended-sediment discharge was derived by sampling suspended sediment at a variety of discharges during the period 1957-67 (USGS 1978). A rating table was developed that was then applied to the 1902-62 time period. Note that sediment estimates derived in this manner are approximate. Pre-dam bedload was estimated at 488 tons per day.

A total sediment input (bedload and suspended load) of about 3,750 tons per day into Lake Oroville suggests that a sediment deficit of about 50 million tons to the Feather River below the dam has occurred between 1967 and the present.

Post dam sediment sampling between 1968 and 1975 resulted in an estimated suspended sediment yield of 42.5 tons per day, demonstrating a dramatic shift between pre- and post dam yield. The net bed material yield from the Low Flow Reach is about 500,000 tons in 50 years.

Figure 7.2-1 shows the relation between streamflow and suspended sediment discharge for the pre-dam years 1957-1962 and1965-1967, and the post dam years 1968-1975. The two pre-dam curves show that the amount of sediment can change significantly from year to year. This is generally in response to major flood events, one that occurred in December 1964 (1965 water year). The post dam curve (1968-75) demonstrates a large drop in suspended sediment discharge for the higher flows that carry most of the sediment. For example a pre-dam flow of 60,000 cfs would transport about 80,000 tons per day. The same post dam flow would transport only 7,000 tons per day.

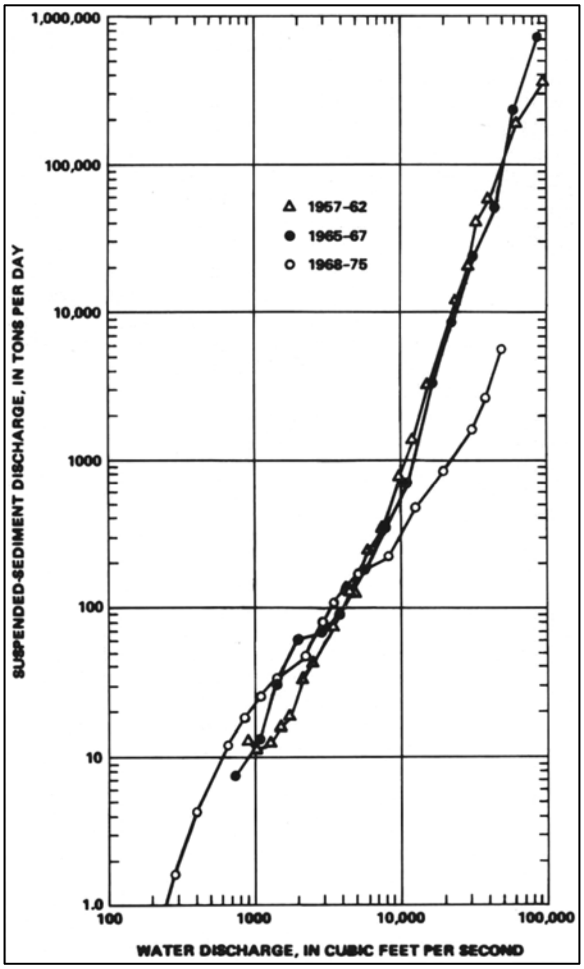

Figure 7.2-1 Relation between Streamflow and Suspended Sediment Discharge, Feather River at Oroville.

The net bed material yield for the High Flow Reach to Honcut Creek is about 3.2 million tons after 50 years. Of this quantity, 2.7 million tons was eroded from the bed and bank, and the remainder introduced as yield from the Low Flow Reach.

7.2.1 Sediment Composition

Bed composition varies in a downstream direction. First there is a general downstream decrease in substrate size. The upper part of the river, from Oroville to Gridley, is mostly a combination of boulders, cobbles, and gravel. Below Gridley to the mouth, the substrate is mostly sand and fine gravel.

Bed composition also varies locally depending on hydraulic and geomorphic variables. Pools tend to have smaller grain sizes than neighboring riffles and runs. For example, fine gravel is present on point bars and riffles below Gridley, but most of the pools, runs, and glides are composed of sand.

Below a dam, there is no sediment replenishment. Finer sediment is more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport results in the gradual coarsening of the bed material.

Bed material was sampled between the Fish Barrier Dam and Honcut Creek. This is the reach where most of the Chinook salmon spawning occurs. Both bulk and surface samples were taken. Tables in the Task 2 report show the bulk sample statistics and surface sampling. Between Gridley and Verona, compositions were determined by visual examination of the bed surface. These are presented in the Task 1.2 report.

Several observations may be made from the bulk sampling data. First, there is a general but dramatic fining of the substrate in the downstream direction. The average, or median grain size of bulk surface gravel samples below the Thermalito Diversion Dam, is about 105mm, about 60mm below the Thermalito Afterbay outlet, and about 35mm at the Honcut Creek confluence.

Second, there is a broad variation in mean gravel size on riffles. The variability occurs both locally on a riffle, and between adjacent riffles. Third, the bed is armored, with a significantly coarser surface layer as compared to the subsurface layer.

Fourth, the bed appears to be coarsening with time. A comparison of 1982, 1996, and 2003 data shows an over all bed material coarsening trend. This trend is shown in the graphs and tables of the Task 2 report.

Water Engineering and Technology (WET 1990 and 1991) also sampled banks, point bars, and river beds. The results of their sample analyses are shown in Table 7.2-1.

Table 7.2-1. Bed Material Grain Size in millimeters.

Site	River Mile	D16	D50	D84	Sorting
Subarmor	56.4	2	20	63	1.7
Subarmor	53.3	2.1	13.6	64	11.2
Bed Armor	50	4.6	32	66	5.5
Subarmor	47.3	1.3	11	35	3.8
Subarmor	40.5	1.2	9	27	5.2
Bed	40.2	.4	.7	1.1	4.7
Bar	37.5	.9	3.3	14	1.6
Bar	34.5	.5	.9	1.6	3.9
Bed	30	.4	.7	1.1	1.7
Bar	29.2	.3	.4	.7	1.7
Bed	19	.5	.8	1.2	1.6
Bed	11.6	.4	.6	.9	
Bed	0	.3	.4	.7	

Between Gridley and Verona, geologic data suggests that, below the movable sand bed, the river is incised into the hydraulic mine slickens.

FLUVIAL-12 modeled changes in median grain size are shown in Figure 7.2-4 for an armored bed. This simulates changes that are expected for the next 50 years. Modeling was also done for a natural bed. The natural bed is finer, and represents pre-project conditions.

The initial grain sizes for the natural bed are quite uniform along the channel reach with only limited spatial variations. At the end of the 50 years, the grain sizes become coarser and less uniform along the channel reach. In time variation, the grain sizes are getting coarser with time. In spatial variation, the grain sizes become less uniform along the channel reach with coarser grain sizes near the upstream end and decreasing sizes toward downstream. In other words, sediment coarsening and bed armoring develops starting from the upstream end and such effects propagate gradually downstream. The simulated grain sizes at the end of the 50-yr time period are similar to the grain sizes in the existing armored layer.

The changes in grain sizes for the natural channel bed and armored channel bed are different. For the natural bed, the average median grain size for the study reach is about 23 mm. After 50 years, the reach-averaged median grain size becomes 60 mm. This scenario models changes expected in the first 50 years after dam closure. To model ongoing changes, the armored bed is used. The reach-averaged median grain size for the existing armored bed is about 60 mm. The simulated median grain size after 50 years is 75 mm. This comparison shows that the coarsening slows down with time. As the bed material of the surface layer becomes coarser, the bed becomes less mobile, less sediment is removed by erosion.

Figure 7.2-4 shows the initial and final mean bed material diameter after a 50-year post dam model run. First, there is a natural decrease in sediment size in the downstream direction, caused by a decrease in gradient and stream power. This is reflected in both the initial and final conditions. The model run shows a dramatic increase in the sediment size after 50 years. The largest increase was directly below the Fish Barrier Dam, with a D50 increase from 120 mm to 190 mm. At RM 62, an instream mining area, the pit becomes finer from deposition, but the area below becomes coarser, from 60 mm to 80 mm. At RM 44 near Honcut Creek, the size increased only slightly from a D50 of 30 mm to about 40 mm.

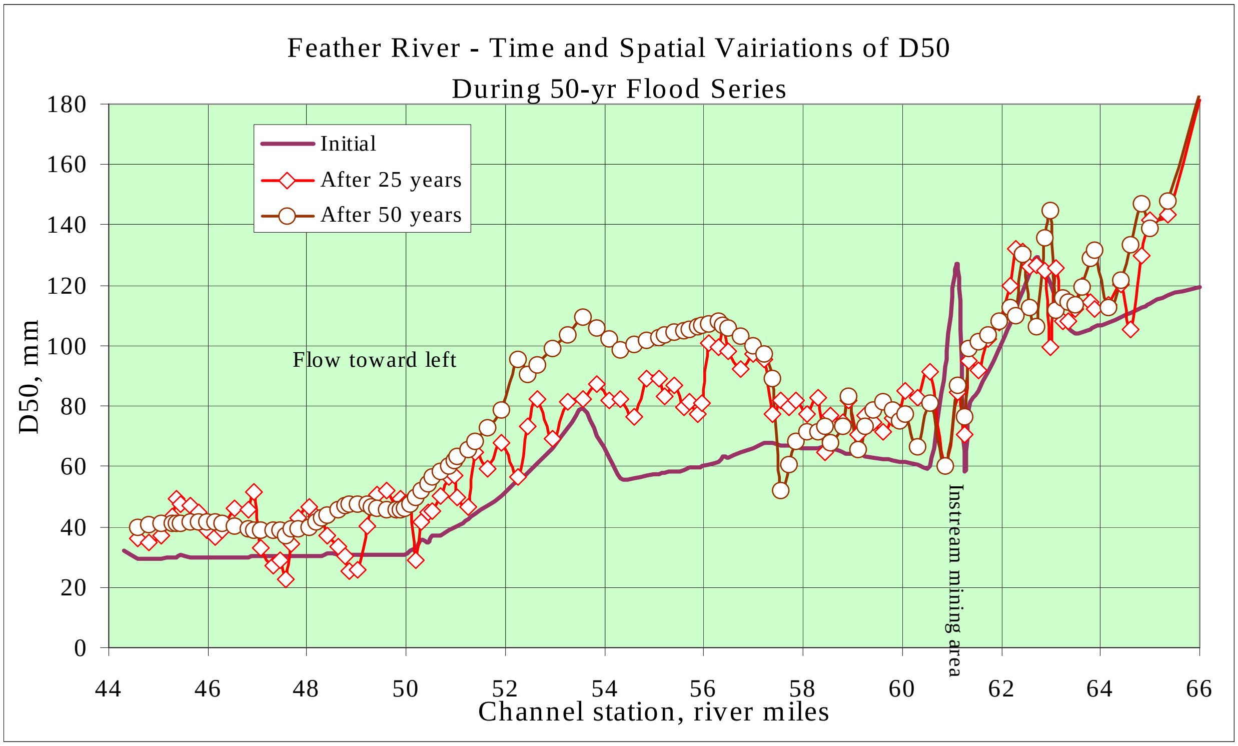

Figure 7.2-4 Time and Spatial Variations of Median Grain Size during the 50 Year Flood Series for Armored Bed.

7.3 INITIATION OF SEDIMENT MOTION

Flow conditions for the initiation of sediment motion were determined for different gravel sizes using the FLUVIAL-12 model. The commonly used criterion for the initiation of sediment motion is the Shields criterion (see Chang 2004 in Appendix A to the Task 7 Report). For river flow in the rough zone, the Shields criterion for incipient motion is as follows.

$$\frac{\tau_c}{(\gamma_s - \gamma)\, d} = 0.06$$

In the equation, τ_c is the critical shear stress for incipient motion, in pounds per square foot; γ_s is the unit weight of sediment (165 lbs/ft^3); γ is the unit weight of water (62.4 lbs/ft^3); and d is the sediment size (feet). The above equation can be written as:

$$\tau_c = (165–62.4)0.06\ d = 6.156d$$

and $\quad d\ (\text{feet}) = 0.162\ \tau_c$

or $\quad d \text{ (inches)} = 1.95 \ \tau_c$.

Therefore, the critical shear for gravel is directly proportional to the effective gravel size.

The shear stress at a point in channel bed is computed by

$$\tau_c = \gamma y S$$

where y is the depth of flow and S is the energy slope.

The Feather River has gradually-varied flow over riffles and pools at all times. The channel bed shear stress varies from riffle to pool and cross section to cross section. At the same cross section, the shear stress also varies from point to point. Usually, the maximum shear stress occurs at the thalweg. Therefore, incipient motion usually starts at the thalweg.

Because of the variation in flow characteristics, the sediment motion occurs at certain bed locations but not at other locations. The average flow condition of a channel reach for the initiation of sediment motion is determined. Under this condition, about half of the cross sections have little or no sediment motion, but the other half still have limited sediment motion, as shown in Figure 7.3-1.

The figure shows that the Low Flow Reach can move larger diameter gravel than the High Flow Reach at the same discharge. For example, at 10,000 cubic feet per second, the low flow reach will begin to transport 1.25 inch gravel, and the High Flow Reach will transport 0.75 inch gravel.

The figure shows that in the Low Flow Reach, incipient motion of the 2-inch gravel occurs at the discharge of 35,000 cfs; and the motion of 3.5-inch gravel is initiated at the discharge of 114,000 cfs. In the High Flow Reach, incipient motion of the 2-inch gravel occurs at the discharge of 72,000 cfs; the 3.5-inch gravel does not move at the discharge of 114,000 cfs. The High Flow Reach has a flatter slope than the Low Flow Reach; it takes more flow to move the same size gravel in the High Flow Reach than in the Low Flow Reach.

The effect of the Project on bed initiation may be estimated using the equations and figures above in conjunction with the flow exceedance diagrams in Section 5. For example, a 10,000 cfs flow capable of transporting 1.25- inch gravel, had a recurrence interval of 13 days per hundred prior to the dam, and 1.3 days after the dam. The

2-inch bed initiation discharge of 35,000 cfs for the Low Flow Reach occurred 1.5 days of every hundred days prior to the dam, and 0.5 days after the dam.

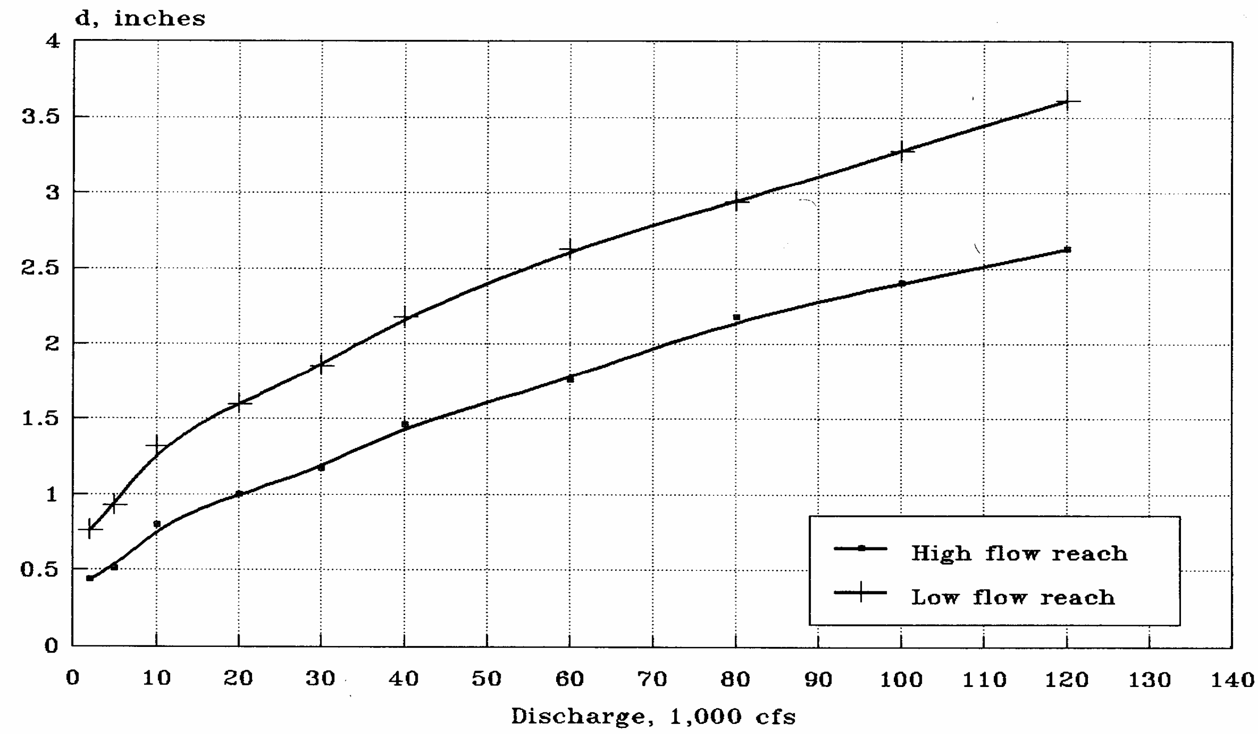

Figure 7.3-1 Sediment grain size in relation to flow discharge at initiation of motion.

8.0 SUMMARY AND CONCLUSIONS

The following sections summarize the findings regarding hydraulic, geomorphic and sediment changes on the lower Feather River below Oroville Dam. Results from all the SP-G2 Study Plan reports were used.

The study results will be used by other studies to help assess the project's ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources.

8.1 HYDRAULIC CHANGES

Dams in California cause changes in the downstream hydraulic regime by capturing and storing high winter flows and subsequently releasing the water during summer months for power and irrigation.

- Many of the changes in hydrology on the Feather River are not a result of the Oroville Project but a combination of other dams and diversions, levees, dredging, timber harvesting, grazing, mining activities, urbanization, and agriculture. Many of these changes occurred prior to the Oroville Project or are ongoing.

- The Low Flow Reach of the Feather River between the Thermalito Diversion Dam and the Thermalito Outfall shows the largest hydraulic changes. The pre – and post Oroville Dam mean monthly streamflow shows that all 12 months are affected significantly by the dam, but the spring snowmelt months have the largest changes.

- Flow exceedance calculations for the Feather River at Oroville gage show that the flow exceeded 99 percent of the time decreased from 950 cfs to 300 cfs from pre- to post dam. The 90 percent exceedance flow decreased from 1,400 cfs to about 300 cfs, and the 50 percent exceedance flow decreased from 3,000 cfs to 350. The flow exceeded one percent of the time changed from 37,000 to 21,000 cfs. Note that the minimum dam flow release changed from about 300 to 600 cfs during the study period, and this will affect the 99 percentile flow.

- Flood frequency calculations show that the pre- and post project flood frequency curves have changed. The 2 year recurrence interval flood decreased from 65,000 to 3,000. The ten year recurrence event decreased from 160,000 to 75,000. The 50 year event decreased from 240,000 to 180,000 cfs.

- The average combined annual diversion from the Oroville Project above Thermalito is about 1,100 cfs. This is about 20 percent of the average annual yield of the Feather River at this point. July has the highest diversion, with the combined diversion averaging 2,600 cfs (1967-98).

- The "Indicators of Hydraulic Alteration" analysis was done on three Feather River gages. The IHA analysis demonstrates pre- and post project changes for 33 hydraulic variables.

- Indicators of Hydraulic Alteration analysis show a high degree of hydraulic alteration for the Low Flow Reach of the Feather River. The main reasons for this are the flood control and storage aspects of Oroville Dam. In addition, the "at Oroville" gage is in the low flow reach. This means that the majority of both the summer and winter flows are diverted around this reach by the Thermalito Diversion Dam. A minimum flow of about 600 cfs occurs most of the year for fish maintenance.

- Summarizing the IHA analysis for the Feather River at Oroville gage, the only variable to show no change was the number of zero-flow days. Only one variable, the date of maximum flow, showed low alteration. A large degree of alteration occurred for all 31 remaining variables.

- The High Flow Reach of the Feather River below the Thermalito outfall shows a lesser degree of alteration than the Low Flow Reach, but some changes are significant. These include a decrease in both high and low flow pulses, a dramatic increase in summer flow, and moderate decreases in winter and spring flows.

- Downstream below Yuba City the degree of alteration attributable to Oroville Dam is less than below the Thermalito outfall primarily because additional streamflow from Honcut Creek, the Yuba River, and the Bear River enter the Feather above the Feather River at Nicolaus gage. This additional streamflow results in the reduction of the degree of alteration caused by Oroville Dam. Dams on the Yuba and Bear rivers were already in place prior to the construction of Oroville Dam, thereby significantly affecting streamflow during the pre-Oroville dam hydrologic period. The alteration in magnitude of mean monthly flows is low for the months October through June, and large only for July, August, and September. There is also a large shift in the timing and discharge of mean minimum flows. The maximum flows were shifted slightly below the median of pre-Oroville flows, thereby altered only to a low degree.

- The IHA analysis shows that mean summer flows have been reduced to 23 percent in July and 24 percent in August of the pre-dam flows at Oroville, but increased 580 percent in July and 1,100 percent in August at Nicolaus. One-day minimum flows have been reduced to 34 percent at Oroville but increased 475 percent at Nicolaus. Mean monthly spring flows have been reduced to 5 percent for Oroville and 50 percent for Nicolaus. Number of river stage reversals increased 132 percent at Oroville but decreased slightly to 95 percent at Nicolaus.

8.2 GEOMORPHIC CHANGES

Fluvial geomorphology is the study of river-related form, function, and evolution. The geomorphology of a stream may be affected by a large number of inter-related factors. These include changes in the watershed, such as rainfall, runoff, sediment yield, vegetation, timber harvesting, road building, fires, agriculture, volcanic eruptions, grazing, and major storm events. Also included are changes in the river, such as dams, hydraulic mining, levees, gravel mining, water diversions, bank protection, dredging, and others. Many of these changes are clearly caused by human activities. Changes may work in concert, resulting in cumulative impacts greater than the individual contributions. Other changes may work counter to each other. The following are summaries and conclusions regarding Project and non-Project related geomorphic changes in the lower Feather River:

- The Feather River today is very different from the Feather River that existed prior to the 1850s. The changes are purely anecdotal, since no survey data are available prior to the 1850s. Mendell (1875, in WET 1991) described conditions prior to human induced changes: “The….. physical condition of the Feather River was something wonderful, when we know that in 1849 it was the counterpart of the present Sacramento in all respects, namely, a succession of deep pools, separated from each other by shallow bars, the water being remarkably clear.”

- The present day Feather River is still profoundly affected by the mining debris. Between 1855 and 1895 several hundred million cubic yards of mining debris were washed into the Feather River system above Yuba City. Over a billion cubic yards washed down the Yuba and Bear Rivers to deposit on the Feather River floodplain. Much of this mining debris, in the form of cobbles and clayey fines called “slickens”, are still present.

- Some of the post mining, pre-dam cross-sections have increased in cross-sectional area up to 400 percent from channel bed and bank erosion. A cross-section at RM 37.4 shows an 80 percent increase in channel area. The average depth increased by almost five feet. A cross-section at RM 41.9 shows a 250 percent increase in area with little change in depth. A cross-section RM 60.4 shows a 15 percent increase in area and about four feet of thalweg lowering. These changes are attributed to channel readjustment and degradation resulting from the cessation of hydraulic mining.

- Post mining degradation has dramatically increased channel capacity and the ability of convey flood water without flooding. The increase in depth and width is characteristic of most of the lower Feather River.

- The bank composition of the Feather River changes through the study reach. The total length of Modesto and Laguna banks are about 55,000 feet or about 8 percent of the total bank length. The Modesto Formation is considered to be geologic control, that is, more resistant to erosion and providing longer term stability with low erosion rates. The slickens, composed of hydraulic mining debris, consist of fine silt with some clay and tends to be erosion resistant. About 160,000 feet of bank or 23.5 percent was mapped as slickens. The slickens occur mostly below Gridley. Flood plain deposits were mapped for 97,000 feet or 14 percent of the total bank. The dredger tailings are coarse cobble and gravel deposit and are somewhat erosion resistant. The tailings are generally present between Oroville and the lower end of the Wildlife Area above Gridley. Tailings were mapped for 66,000 feet or almost 10 percent of the bank. The remainder of the banks are depositional, consisting of gravel and sand bars that normally occur on the inside banks of eroding bends.

- Both the cobble banks and slickens, remnants of mining activity, have increased bank stability and reduced bank erosion. Between Oroville and Gridley, cobbles and coarse gravel dredge tailings constitute most of the banks, slowing the bank erosion process. Below Gridley, slickens rich in cohesive clay, slow bank erosion. Less bank erosion means impacts on meander rates, riparian succession, and sediment in the stream. On the average, the bank erosion rate on the Feather River of about 1.2 feet per year is about one order of magnitude less than on the Sacramento River.

- The post hydraulic mining river has become wider and deeper. Cross - section analyses by the USGS (1972) shows that the channel thalweg has been scoured down as much as 6 feet, and the cross - sectional area has increased as much as 400 percent in places between 1909 and 1970. Most of this entrenchment is an adjustment to the reduction in the post mining sediment supply. The construction of levees for flood protection along much of the reach is also a factor. The levees concentrate in-channel flow, increase sediment transport capacity, and scour the channel.

- Meander rates have been reduced as a result of decreased bank erosion. Meandering is the primary source of stream mesohabitat diversity. Meandering is primarily responsible for the creation of oxbow lakes, multiple channels, side channels, islands, point bars, large woody debris, riffle and pool habitat, and other features.

- Bank erosion sites were identified by shifts in bank line, and the average amount of bank recession was calculated by dividing the acreage of bank movement by the number of years between bank lines. The sites selected by river mile and the area of bank line migration are shown in Appendix A Table 1 for 1909-1967 and Table 2 for 1967-2001. The total acreage of change between 1909 and 1967 was 1,050 acres for a rate of 18.1 acres per year or an average of 2.26 feet./year. The total acreage of change between 1967 and 2001 was 460 acres for a rate of 13.5 acres per year or an average of 1.69 feet./year.

- The rate of channel migration for the Feather River is very low especially when compared to the Sacramento River between Chico and Colusa where the average rate of migration is 6.7 feet/year or Red Bluff to Chico with an average rate of 14.2 feet./year (DWR 1994). The Feather River has a relatively narrow meander belt and also is currently partially entrenched into the slickens deposits of hydraulic mining debris. The average rate of meander has decreased since the completion of Oroville Dam. The most likely reason for this reduction is the decrease in the frequency of channel forming flow events.

- Between the Thermalito outfall and Honcut Creek rip-rap occurs extensively on both banks. Over 20,000 feet of rip-rap or 13 percent of the bank is rip-rapped in this 14.7 mile stretch. Between Honcut Creek and Sunset Pumps there is about 10,000 feet of rip-rap, or18 percent of the banks, in this 5.2 mile stretch. Between Sunset Pumps and Yuba City 7250 feet of the right bank but only 250 feet of the left bank is rip-rapped. The riprap occurs mainly on the outside of bends against the levee on the right bank and at bridges. A total of just over 6 percent of the bank is rip-rapped in this 11 mile stretch. Riprap below Yuba City is common but not extensive. There are over 25,000 feet of rip-rap with most occurring on the left bank along the levee in the lower 7 miles. About 8 percent of the banks are rip-rapped in the 28 mile stretch from Yuba City to Verona.

- Overall about 64,000 feet or10 percent of the banks of the Feather River are rip-rapped.

- The reach near Thermalito Afterbay has been extensively mined for gravel. As a result, this area has been subjected to greater changes in river planform, bank erosion, channel migration, and degradation than other areas. This is because of the disruption in channel profile and cross-section, resulting in sediment deposition within the mining areas and scour and degradation in the areas above and below.

- The installation of Oroville Dam disrupted the frequency of an established channel-forming bankfull discharge. The pre-dam bankfull discharge (2-year event) for the Feather River at Oroville gage was about 65,000 cfs. The post dam 2-year recurrence interval event for the Low Flow reach is about 2,000 cfs, a much smaller event that is not capable of transporting significant quantities of bedload or erode river banks. The 65,000 cfs flow now occurs at a lower frequency level of about every ten years. The High Flow Reach now has a bankfull discharge of 26,000 cfs, also significantly smaller than the pre-project event of 65,000 cfs.

- Bed material was sampled between the Fish Barrier Dam and Honcut Creek. This is the reach where most of the Chinook salmon spawning occurs. Both bulk and surface samples were taken. Tables in the Task 2 report shows the bulk sample statistics and surface sampling. Several observations may be made from the bulk sampling data. First, there is a general fining of the substrate in the downstream direction. The average, or median grain size below the Thermalito Diversion Dam, is about 105mm, about 60mm below the Thermalito Afterbay outlet, and about 35mm at the Honcut Creek confluence. Second, there is a broad variation in mean gravel size on riffles. The variability occurs both locally on a riffle, and between adjacent riffles. Third, the bed is armored, with a significantly coarser surface layer as compared to the subsurface layer. Fourth, the bed appears to be coarsening with time. A comparison of 1982, 1996, and 2003 data shows an overall bed material coarsening trend. This trend is shown in the graphs and tables of the Task 2 report. Between Gridley and Verona, compositions were determined by visual examination of the bed surface. These are presented in the Task 1.2 report.

- The channel between the Fish Barrier Dam and Honcut Creek has become armored. Some of this armoring can be attributed to post mining degradation, but most of the armoring is caused by the capturing of sediment in the upstream reservoirs including Lake Oroville. Armored beds are a result of a loss of sediment supply and the removal of the finer bed material by high flows. Finer sediments are more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport has resulted in the gradual coarsening and armoring of the bed material. In some places, the bed armoring may be too coarse for the salmon to build redds. The largest increase in size was directly below the Fish Barrier Dam, with a D50 increase from 120 mm to 180 mm and at River Mile 56, with an increase from 60mm to 110mm.

- The river continues to degrade in the post project period, but at a slower rate than the pre-dam period. As part of Task 3, 58 cross-sections surveyed by the USGS in 1970 were compared to the 1997 data. This roughly approximates the post Oroville project period. The channel width narrowed on 10 cross-sections (17 percent), widened on 22 (38 percent), and showed no change on 26 (45 percent). In this period, 31 cross-sections degraded, 12 sections showed no change, 8 aggraded, and 7 were indeterminate.

- The average post Oroville Dam degradation is -0.66 feet averaged by cross-section, or -1.0 averaged by river mile. This results in a rate of about 0.04 feet per year, or about half of the 0.08 1907 to 1997 rate.

- Bank erosion rates were calculated using ortho-rectified aerial photos of various dates. Pre- to post project data shows a 28 percent reduction in bank erosion. The reduction cannot be attributed to the project alone, since about 10 percent of the eroding banks were protected by rock riprap at some point during the study period.

- Some eroding banks have increased rates of post dam erosion. It is not clear why, but several possibilities exist. Bank erosion rates typically increase with a decrease in the radius of curvature and as these banks continue to erode, the radius decreases. A second possibility is that a more erodible soil type has been encountered. Third, ranch management may be increasing bank erosion. For example, irrigation resulting in saturated banks and seepage will generally promote bank failure.

- Measurements from aerial photos in Task 6 shows that the average sinuosity of the study reach is 1.29. The Thermalito Diversion Dam to Yuba City Reach is about 1.4, and the Yuba City to Verona is 1.16.

- The change in sinuosity attributable to Project facilities was investigated in Task 6 by comparing pre- and post Project maps and photographs dating from 1907 to 2001. The total amount of change was small. Most of the changes in sinuosity occurred in the early 1900s. There have been no significant changes in sinuosity since the Oroville Facilities were completed in 1967. This indicates that any change in sinuosity attributable to the Oroville Facilities must also be small.

- As part of Task 7, the FLUVIAL-12 modeling of channel bed profiles were done to predict changes over the next 25 and 50 years between RM 67 and RM 44. Both water-surface and channel bed changes are expected to occur. The modeling shows that degradation will continue, but at a progressively slower rate. The future changes are limited by bed and bank armoring, which in turn, will reduce future bed erosion and sediment yield.

- The overall channel gradient for this reach will not change significantly. However, the model predicts that the channel thalweg will smoothen with time.

8.3 CHANGES IN SEDIMENT

- All of the bed material load and most of the suspended sediment inflow into the study reach is cut off by Oroville Dam. Study Plan Report SPG-1 estimates the amount of sediment from upstream reaches deposited in the reservoir to be about 16,900 acre-feet from 1967 to 2003. This is the deficit amount of sediment to the lower river that can be attributed to Project operations. This amount is equivalent to covering the 67 miles of channel with 6 to 9 feet of sediment.

- The amount of sediment transport is less than pre-Dam conditions. Most of the sediment transported in the lower Feather River is from bed and bank erosion with minor contributions from tributaries. Sediment transport data were available from the U.S. Geological Survey (1978) from 1902-, and for a short time period directly after the construction of project facilities. The average annual pre-dam sediment yield at the Feather River at Oroville gage was estimated to be 3,264 tons per day (1902-62). The post dam yield (1968-75) was estimated at 42.5 tons per day.

- Bed material was sampled between the Fish Barrier Dam and Honcut Creek as part of Task 3. This is the reach where most of the Chinook salmon spawning occurs. Both bulk and surface samples were taken. Between Gridley and Verona, compositions were determined by visual examination of the bed surface. The samples were compared with sampling done in 1982, 1983, and 1995. A coarsening trend, with armoring of the riffles, is evident. The mean particle diameter is significantly coarser than what is considered ideal for salmon spawning.

8.4 FLUVIAL MODELING

- Dr. Howard Chang developed a FLUVIAL-12 model of the Feather River between the Thermalito Diversion Dam and Honcut Creek. The model shows expected changes in sediment, sediment delivery, bed material size, and other parameters for the next 25 and 50 years.

- The 25 and 50 year FLUVIAL-12 model runs show that the amount of sediment delivery will decrease with time. This is a result of the progressive movement of sediment downstream with no replenishment. The combination of armoring and less bed material load will result in a more stable planform, coarser bed material, and less sediment movement.

- The model was run using a number of different sediment transport equations. The Engelund-Hansen equation was selected because the results most closely resembled bed material load transport data measured by the USGS (1978).

- The pattern of sediment delivery for the next 50 years according to FLUVIAL-12 shows a sharp rise in delivery in the High Flow Reach just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary. The net bed material yield is about 2.6 million tons after 50 years. Of this quantity, about 2.1 million tons was from bed erosion in the reach. The remaining 0.5 million tons was introduced load from the Low Flow Reach.

- The pattern of sediment delivery shows a sharp dip at the Robinson gravel mining pond near RM 61. The low levee separating the pond and the river has been breached, and most of the river flows into the pond. Most of the bed material load from above is deposited in the pit. Sediment starvation below the pit results in bed armoring and an increase in mean gravel size on Robinson Riffle compared to riffles above and below. Only a small part of the streamflow now flows across the Robinson Riffle area, reducing the quality of the spawning habitat.

- The amount of bed material load in the Feather River passing the Thermalito Outfall (Low Flow Reach) is modeled at 500,000 tons, or about 10,000 tons per year, or 27 tons per day. This is about half of the yield calculated by the USGS between 1968 and 1975. The yield is primarily a result of channel erosion since bed material is trapped by the upstream Dams including Oroville Dam.

- Lateral migration of channel bends are predicted by the FLUVIAL-12 model. The amount of bank erosion in the Low Flow Reach is small, a reflection of the stable banks consisting of erosion resistant bedrock, terrace deposits, and cobble dredger tailings. The largest lateral bank movement occurs on the left bank directly above the Robinson gravel mining pit. Most of the bank erosion in the modeled reach occurs in the High Flow Reach in three places within several miles above the Feather River's confluence with Honcut Creek. Cross-sections in this area show lateral migration. However, because of the placement of cross-sections, a better prediction of future lateral migration is based on aerial photography interpretation in the Task 6 Report.

- The modeling shows that spawning size gravel are transported at moderate and high flows that occur a number of times each ten year period. One inch gravel begins to move at about 5,000 cfs in the Low Flow Reach, and 20,000 cfs in the High Flow Reach. Three inch gravel begins to move at 80,000 cfs in the Low Flow and over 130,000 cfs in the High Flow Reach.

- The location of sediment traps is important in designing Resource Actions such as gravel augmentation projects. Abandoned instream gravel mining areas and pits may capture spawning gravel injected into the river above.

- Coarsening occurs over most of the modeled reach. Since coarsening is related to an increase in roughness according to standard hydraulic equations, the roughness will also increase as a result of Project operations.

- The coarsening and armoring attributed to operation of the Oroville Facilities is expected to change the stream type to some degree. A C4 or C5 may, over time, become a C3 as the predominant substrate changes from sand and gravel to cobble. Similar changes can be expected for the other stream types.

- The model was run using two initial bed material conditions. One run used natural, unarmored bed material. This run was used to simulate changes that occurred immediately after dam closure to the present. The second run used armored bed material for input. This models ongoing changes occurring now and in the future.
- The initial grain sizes for the natural bed are quite uniform along the channel reach with only limited spatial variations. At the end of the 50 years, the grain sizes become coarser and less uniform along the channel reach. In time variation, the grain sizes are getting coarser with time. In spatial variation, the grain sizes become less uniform along the channel reach with coarser grain sizes near the upstream end and decreasing sizes toward downstream. In other words, sediment coarsening and bed armoring develops starting from the upstream end and such effects propagate gradually downstream.
- The changes in grain sizes for the natural channel bed and armored channel bed are different. For the natural bed, the average median grain size for the study reach is about 23 mm. After 50 years, the reach-averaged median grain size becomes 60 mm. This scenario models changes expected in the first 50 years after dam closure. To model ongoing changes, the armored bed is used. The reach-averaged median grain size for the existing armored bed is about 60 mm. The simulated reach-average median grain size after 50 years is 75 mm.
- The Low Flow Reach can move larger diameter gravel than the High Flow Reach at the same discharge. For example, at 10,000 cubic feet per second, the low flow reach will begin to transport 1.25 inch gravel, and the High Flow Reach will transport 0.75 inch gravel.
- The effect of the Project on bed initiation may be estimated using modeling results from FLUVIAL-12. For example, a 10,000 cfs flow capable of transporting 1.25- inch gravel, had a recurrence interval of 13 days per hundred prior to the dam, and 1.3 days per hundred after the dam.

9.0 REFERENCES

Chang, Howard. January 2004. *Fluvial Modeling Study of Feather River Responses to Oroville Dam and Related Issues*. Appendix A to "Task 7- Hydraulic and Sediment Transport Modeling of the Feather River". Draft Final Report prepared for the Dept. Water Resources.

Department of Water Resources. April 2004. *Effects of Project Operations on Geomorphic Processes Upstream of Oroville Dam*. Draft Final Report.

-----. 1994. *Sacramento River Bank Erosion Investigation*. Northern District Memorandum Report.

-----. 1982. *Feather River Spawning Gravel Baseline Study.* Northern District Report. 142 pages with plates and figures.

-----. 1970. *Pre-Operation Water Quality Conditions State Water Project, Volume I Oroville Field Division and Lower Feather River*. 101pp.

-----. 1969. Maps and Cross-Sections of the Feather River on File with DWR Photogrammetry. Sacramento.

-----. 1965. Maps and Cross-Sections of the Feather River on File with DWR Photogrammetry. Sacramento.

James, A. 1989. *Sustained Storage and Transport of Hydraulic Gold Mining -Sediment in the Bear River, California.* M.S. Thesis.

Mount, J. F. 1995. *California Rivers and Streams: The Conflict between Fluvial Process and Land Use*. University of California Press, Berkeley and Los Angeles, California. 359pp.

Rosgen, D. L. and H. L. Silvey. 1996. *Applied River Morphology*. Wildland Hydrology. Pagosa Springs, CO. Printed Media Companies. Minneapolis, Minnesota.

The Nature Conservancy. 2001*. Indicators of Hydrologic Alteration, User's Manual*. The Nature Conservancy and Smythe Scientific Software. 53pp.

U.S. Army Corps of Engineers. 1997. Topographic maps and Cross-Sections Prepared for the Sacramento and San Joaquin River Basins Comprehensive Study. Sacramento District.

-----. 1907 to 1911. California Debris Commission Surveys and Maps Showing Topography and Cross-sections.

U.S. Geological Survey. 2004. Water Resources Data Internet Web Pages.

-----. 1978. *Sediment Transport in the Feather River, Lake Oroville to Yuba City, California*. Menlo Park, California.

-----. 1972. *Determination of Channel Capacity of the Feather River between Oroville and Honcut Creek, Butte County, California*. Menlo Park, California. 54pp.

Water Engineering and Technology. 1991. *Geomorphic Analysis and Bank Protection Alternatives Report for Sacramento River, Feather River, Yuba River, Bear River, and American River.* Fort Collins, Colorado. 327 pp.

. -----.1990. *Geomorphic Analysis and Bank Protection Alternatives Report for Sacramento River (RM 78-194) and Feather River (RM 0-28).* Fort Collins, Colorado. 278 pp.

Wildman, Nancy A. 1981. *Episodic Removal of Hydraulic-Mining Debris, Yuba and Bear River Basins, California.* Masters Thesis. Department of Earth Resources. Colorado State University, Fort Collins, Colorado. 107pp.